

Lighting Economics

25

THE ROLE OF ECONOMIC ANALYSIS IN LIGHTING¹⁻⁵

Lighting must be responsive to all the needs of the user, including economic needs. In fact, economic needs often drive the decision-making process when lighting systems are designed and purchased. Unfortunately, economic concerns are often considered the antagonist of aesthetic and visual concerns. The lighting professional tends to draw up a list of those criteria and needs that are considered essential, and then begins the complicated process of identifying priorities and determining those that can be accommodated by the budget.

Rather than considering economic analysis as the antithesis of engineering analysis or aesthetic design, it should be viewed as a framework within which all of the needs of the various clientele can be taken properly into account. For example, when a worker's vision is impaired by disability glare, reduced productivity is an economic consequence. A decision to improve the lighting could be based on the economic needs of the owner. When the lighting of an office building atrium fails to complement the architecture of the space, the rental value fails to achieve its potential. Again, a decision to improve the lighting is an economic decision. Thus, correctly taking care of economic needs can ensure that the other lighting needs are properly considered.

A comprehensive lighting economic analysis for new or existing systems should:

- Compare alternative systems
- Evaluate maintenance techniques and procedures
- Evaluate energy management technologies and strategies
- Determine the effect of lighting on other building systems
- Plan budget and cash flow
- Simplify lighting system characteristics to a cost measure
- Determine the benefit of lighting relative to its cost (cost-benefit analysis)

LIGHTING COST COMPARISONS

Many metrics and techniques have been proposed over the years for comparing the cost of one lighting system with that of another. These methods can be classified into two cate-

gories: first-level and second-level analysis methods (Figure 25-1). The distinction between the two groups is that the first-level methods do not consider the time value of money. The term "time value of money" refers to the fact that one dollar today is not equivalent to the promise of one dollar at a specified time in the future.

The Cost of Light

The simplest economic analysis consists of one rule: the initial costs are compared and the least expensive is chosen. Thus, if lamp A costs \$1.20 and lamp B costs \$1.00, lamp B is selected. If the lamps are identical in performance, this may be a sufficient analysis. However, if lamp A produces 1000 lumens (lm) and lamp B produces only 800 lm, then one might choose A based on a comparison of the cost per lumen (A, 0.12 cents/lm; B, 0.125 cents/lm). On the other hand, lamp A might have a rated life of 1000 h as compared with 1100 h for lamp B, so a further refinement of the calculation would be necessary.

Both costs and benefits must enter the analysis in order to obtain a meaningful result. The process of providing the desired lighting involves the expenditure of money for a number of products (e.g., lamps, luminaires, and wire, and services such as labor and electricity) to obtain certain benefits, namely light. This was recognized early in the history of electrical lighting, and basic measures of lighting value have been developed based on the idea of cost per unit of lighting delivered. This is the traditional "cost of light" and would logically be expressed in dollars per lumen hour. Because the cost per lumen hour of a typical general lighting system is very small, the unit of dollars per million lumen hours is usually used instead.

The cost of light can be expressed by the following equation:

$$U = \frac{10}{Q} \left(\frac{P + h}{L} + WR \right) \quad (25-1)$$

where

U = unit cost of light for a lamp (dollars/ 10^6 lm $\times$ h),

Q = mean lamp flux (lumens),

P = lamp price (cents),

h = labor cost to replace one lamp (cents),

L = average rated lamp life (thousands of hours),

W = mean input power per lamp (lamp and losses) (watts),

R = energy cost (cents/kilowatt-hour).

Figure 25-1. Lighting Cost Comparison Methods

First-Level Analysis Methods*
Cost of light
Simple payback
Simple rate of return
Second-Level Analysis Methods
Life-cycle cost-benefit analysis
Savings-investment ratio
Internal rate of return

* Generally not recommended for large or complex projects.

The cost of light is calculated by multiplying the average light output in lumens by the life of the lamps and dividing the result into the total owning and operating costs for the same time period. Equation 25-1 shows the simplest formulation. The cost-of-light method can be used to compare two competing lamps for use in the same lighting system or to evaluate a retrofit lamp such as a compact fluorescent lamp as an alternative to an existing incandescent lamp.

Note that this equation contains no information about the luminaire in which the lamp is housed. Care must be exercised in extending its use to choices between systems containing different luminaires. Suppose, for example, a manufacturer introduces a new lamp as an efficient replacement for metal halide lamps. By performing the calculation of Equation 25-1 twice, once for a metal halide lamp and once for the new lamp, one could determine approximately the cost to produce one million lumen hours with each of the two lamps individually. However, if the lamps differed appreciably in physical characteristics such as size, shape, and operating temperature, the luminaires that house them might also differ appreciably in efficiency, cleaning requirements, intensity distribution, or maintenance characteristics. Each of these differences could affect the cost of owning and using the system.

Another weakness of the cost-of-light method is that it does not consider the time value of money. However, when the life of the project is short (say, two years or less), as occurs in seasonal or other temporary lighting, interest rates have little effect on the analysis, and a method that ignores them can still be useful. Also, if interest rates are very low or are considered separately (as in a project involving an expense rather than a capital expenditure), then ignoring the time value of money may be appropriate.

Simple Payback

Simple payback is a first-level method commonly used in the lighting industry today for comparing and evaluating a lighting project or proposal. Payback offers information about the amount of time required for an investment or initial outlay to be paid off. It is defined as the initial cost of a

system divided by the annual cash flow or saving that the system engenders. Simple payback is calculated by the following formula:

$$P = \frac{I}{A} \quad (25-2)$$

where

P = payback period (years),
 I = incremental investment (dollars),
 A = incremental annual cash flow.

The term "incremental" in the above definitions for I and A indicates a comparison of one system to another. Two types of comparisons are possible: comparing a proposed replacement system to an existing system, or comparing design alternatives for a new space in which there is no existing system. The former is the more common use of the simple payback concept in lighting.

Frequently, questions arise concerning the desirability of replacing existing lighting with a new technology. Will a system pay for itself and how long will it take to do so are the most commonly asked questions. For example, the owner of an office building may estimate that a certain lighting modification saves about \$2000 in energy costs annually. The expense associated with purchasing and installing the modification is estimated at \$11,000. Thus the simple payback period would be

$$P = \$11,000 / \$2000 = 5.5 \text{ yr}$$

Those who like the simple payback method argue that it is easy to use and a simple way to determine the profitability of a proposed action. In fact, however, it is actually a risk assessment tool posing as a profitability metric. This is seen by examining the question the method answers. It does not answer the question, is a certain investment profitable? Rather, it responds to the concerns of the person who is unsure about the future and hopes to recoup the investment as soon as possible. If getting money back is the primary concern, then there is no reason to make the investment at all. If no investment is made, then that money is available immediately, and the payback is zero years, the ideal result of a simple payback calculation.

Another problem with this method is that it fails to consider what happens after the investment is paid back. For example, if the savings from system A (which has a shorter payback than system B) decline sharply each year after the payback period, but the savings of system B remain steady, the payback method has led to the choice of an inferior alternative. A similar situation is encountered if the systems have different lengths of economic life. Therefore the payback method cannot be used when the alternatives have nonuniform cash flows, nor is it appropriate for assessing options having different lives.

As with all first-level methods, simple payback does not

consider the time value of money. Therefore, like the cost-of-light method, simple payback is best suited for short-lived projects for which interest rates have little importance. Simple payback can also be helpful as an initial screening method for projects of longer duration: if a system pays back within some specified short period (typically one or two years), then it is extremely likely to be profitable and can be accepted with no further analysis. However, a project that does not pass such a test should not be rejected, since it may still be profitable. Instead, the project should be subjected to more rigorous analysis based on a second-level method.

Simple Rate of Return

The simple rate of return is simply the reciprocal of the payback:

$$\text{ROR} = \frac{A}{I} \quad (25-3)$$

where

ROR = rate of return,
A = incremental annual cash flow,
I = incremental investment.

Thus if a system saves \$20,000/yr and requires an initial investment of \$100,000, its simple rate of return is \$20,000/\$100,000, or 20%, equivalent to a 5-yr payback. The advantages and disadvantages of this method are identical to those of the payback method. It is simple to apply and understand, but it cannot deal with nonuniform savings streams or unequal lives.

Life-Cycle Cost-Benefit Analysis (LCCBA)

The first-level methods are attractive due to their simplicity. However, they may lead to serious errors, and thus they are generally not recommended for large or complex projects. Of the second-level methods, life-cycle cost-benefit analysis (LCCBA) has emerged as the most robust method and is approved by experts in managerial economics from all industries.⁶⁻⁸ Therefore, LCCBA is presented here as the economic analysis method recommended by IESNA.⁹

LCCBA uses a differential cost to give a direct comparison of systems under consideration. As with all second-level methods, the time value of money is considered. An outline of this method for comparing new interior lighting systems is illustrated by the worksheet in Figure 25-2. Within the format of that figure, two lighting system alternatives (systems 1 and 2) are compared. Both systems must be assumed to provide equal functional benefits or to fulfill all functional requirements, and any additional benefits either system provides have no economic value to the owner. The method is easily expanded using the same format if comparison of additional options is desired.

The first step in the LCCBA process is to complete the worksheet in Figure 25-2 for each system under consideration. The notes give estimates and default values to be used only as a last resort for values that are not available by any other means. Since initial costs and annual power and maintenance costs occur at different times, they cannot be directly compared. The second step, then, is to put all terms into their time equivalents to allow comparison. The following equations are used to take into consideration the time value of money.

The single present-worth factor is calculated by

$$P = F \times \frac{1}{(1+i)^y} \quad (25-4)$$

where

P = present worth, or the equivalent value at present (dollars),
F = future worth, or the amount in the future (dollars),
y = number of years,
i = opportunity or interest rate as a decimal fraction (5% equals 0.05).

The single present-worth factor finds a value today, *P*, which is equivalent to a value in the future, *F*. In other words, one is equally willing to be paid *P* dollars today as to pay *F* dollars at a time *y* years in the future.

The uniform present-worth factor is determined by the following equation:

$$P = A \times \frac{(1+i)^y - 1}{i(1+i)^y} \quad (25-5)$$

where

P = present worth, or the amount at present (dollars),
A = amount of an annual payment (dollars),
y = number of years,
i = opportunity or interest rate as a decimal fraction.

This equation converts a stream of equal annual amounts into a single present value. There is no cost difference between making annual payments of *A* dollars for the next *y* years and paying *P* dollars today.

The uniform capital recovery factor is

$$A = P \times \frac{i(1+i)^y}{(1+i)^y - 1} \quad (25-6)$$

where

A = amount of an annual payment (dollars),
P = present worth, or amount at present (dollars),
y = number of years,
i = opportunity or interest rate as a decimal fraction.

The reciprocal of the uniform present-worth factor, the uniform capital recovery factor, is the annual amount which, in a uniform stream, is equivalent to *P* dollars today.

Figure 25-2. Worksheet for LCCBA

	System 1	System 2
A. Initial Costs		
1. Lighting system—initial installed costs, all parts and labor:	_____	_____
2. Total power used by lighting system (kW):	_____	_____
3. Air-conditioning tons required to dissipate heat from lighting (kW / 3.516):	_____	_____
4. First cost of air-conditioning tons in line A3 @ \$ _____ / ton:	_____	_____
5. Reduction in first cost of heating equipment:	_____	_____
6. Utility rebates:	_____	_____
7. Other first costs engendered by the presence of the lighting systems:	_____	_____
8. Subtotal mechanical and electrical installed cost:	_____	_____
9. Initial taxes:	_____	_____
10. Total costs:	_____	_____
11. Installed cost per square meter (memo):	_____	_____
12. Watts of lighting per square meter (memo):	_____	_____
13. Residual (salvage) value at end of economic life:	_____	_____
B. Annual Power and Maintenance Costs		
1. Luminaire energy (operating hours × kW × \$ / kWh):	_____	_____
2. Air-conditioning energy (operating hours × tons × kW / ton × \$ / kWh):	_____	_____
3. Air-conditioning maintenance (tons × \$ / ton):	_____	_____
4. Reduction in heating cost:	_____	_____
5. Reduced heating maintenance (MBtu × \$ / MBtu):	_____	_____
6. Other annual costs engendered by the lighting system:	_____	_____
7. Cost of lamps annually (see notes):	_____	_____
8. Cost of ballast replacement (see notes):	_____	_____
9. Luminaire washing cost (number of luminaires × cost per luminaire):	_____	_____
10. Annual insurance cost:	_____	_____
11. Annual property tax cost:	_____	_____
12. Subtotal, annual power and maintenance (with income tax):	_____	_____
13. Income tax effect of depreciation:	_____	_____
C. Comparisons		
1. Present worth: $A_{10} + P(A_{13}) + P(B_{12} + B_{13})$	_____	_____
2. Annual cost: $A(A_{10}) + A(A_{13}) + B_{12} + B_{13}$	_____	_____

In section C, P represents the present worth factor, and A represents the annual cost factor described in the text

The uniform sinking fund factor is determined by

$$A = F \times \frac{i}{(1+i)^y - 1} \quad (25-7)$$

where

F = future worth, or amount in the future (dollars),
 A = amount of an annual payment (dollars),
 y = number of years,
 i = opportunity or interest rate as a decimal fraction.

This equation finds an equal stream of annual amounts that is equivalent to some specified amount at a specific time in the future. Again, there is no cost difference between the offer of F dollars y years from now and the offer of A dollars each year for y years.

The present worth of an escalating annual cost can be determined by one of several formulas. The general form is

$$P = \sum_{k=1}^y A \frac{(1+r)^k}{(1+i)^k} \quad (25-8a)$$

where

P = present worth, or amount at present (dollars),
 A = initial annual payment (dollars),
 y = number of years,
 i = opportunity or interest rate,
 r = rate of escalation, or percentage by which the annual payment increases each year, as a decimal fraction (5% equals 0.05).

If the interest rate i and the rate of escalation r are the same, the above equation becomes

$$P = A y \quad (25-8b)$$

If i and r are different, Equation 25-8a becomes

$$P = A \times \frac{(1+r)[(1+i)^y - (1+r)^y]}{(1-r)(1+i)^y} \quad (25-8c)$$

The systems can now be compared in either of two ways. Either the residual value (line A13 from Figure 25-2) and

annual costs (lines B12 and B13) can be converted to their present values using Equations 25-4 and 25-5, respectively, or the total initial cost (line A10 from Figure 25-2) and the residual value (line A13) can be converted to annualized amounts using Equations 25-6 and 25-7, respectively. Once all costs for a system have been converted to either annual equivalents or present-worth equivalents, they can be summed to obtain a single value for each system. Systems can now be compared on the basis of a single number. These approaches are summarized in section C of Figure 25-2.

An additional subtlety can be injected if an estimate is available for the expected rate of cost increase over time for any of the costs (for example, if it is predicted that the cost of energy will increase 5% each year over the planning horizon). Using Equation 25-8a, b, or c, escalation rates of this type can be applied to the annual costs of lines B1 through B11 of Figure 25-2.

Notes on the Use of Equations 25-4 through 25-8. Equations 25-4 through 25-8 serve to make explicit the notion that one dollar today is not equal in value to one dollar a year from now. This is easily seen from the example of \$100 deposited in an account that bears 5% annual interest. At the end of one year, the amount has grown to \$100 plus 5%, or \$105. Thus it can be said that \$100 today is in some sense equivalent to \$105 one year from today. In terms of Equation 25-4,

$$P = F \times \frac{1}{(1+i)^y}$$

$$\$100 = \$105 \times \frac{1}{(1+0.05)^1}$$

If it is desired to know how much would need to be deposited in this account today in order to yield \$100,000 in 20 years, Equation 25-4 can again be applied:

$$P = \$100,000 \times \frac{1}{(1+0.05)^{20}}$$

$$P = \$37,689$$

Again, \$37,689 today and \$100,000 in 20 years are considered equivalent at an interest rate of 5%. This equivalence holds for any 20-year investment at 5% interest, including lighting systems.

Similarly, time equivalents can be computed for streams of equal annual payments or receipts. For example, if the depositor in the previous example does not have \$37,689 today to deposit in an account, it might be desirable to know how much money must be set aside each year over the next 20 years in order to have \$100,000 on hand at the end of that period. Equation 25-7 is used:

$$A = F \times \frac{i}{(1+i)^y - 1}$$

$$A = \$100,000 \times \frac{0.05}{(1+0.05)^{20} - 1}$$

$$A = \$3024$$

Twenty annual payments of \$3024 are equivalent to \$100,000, 20 years from now, if the interest rate is 5%. One might be willing to pay \$3024 annually in maintenance costs to avoid the need to replace a lighting system at a cost of \$100,000 after 20 years.

To illustrate the use of Equation 25-5, consider a lighting retrofit that saves \$10,000 per year in energy costs each year over the next 10 years. How much should one be willing to pay for this retrofit today if the interest rate is 6%?

$$P = A \times \frac{(1+i)^y - 1}{i(1+i)^y}$$

$$P = \$10,000 \times \frac{(1+0.06)^{10} - 1}{0.06(1+0.06)^{10}}$$

$$P = \$73,601$$

So \$73,601 today is equivalent to a stream of equal payments (or receipts) of \$10,000 annually for 10 years at 6% interest.

NOTES ON THE LCCBA WORKSHEET

This section contains some explanatory information for using the LCCBA worksheet in Figure 25-2. Since the analysis of lighting system economics is predominantly the analysis of costs, the convention used is costs are positive, and revenues, savings, and benefits are negative. Estimates and default values listed should be used only as a last resort if actual figures are not available.

This worksheet procedure can be used to analyze new construction as well as lighting retrofits. For lighting retrofits, the existing system can be identified as System 1, and each line item should reflect the associated cost. Most of the initial costs for the existing system are zero, unless maintenance to the existing lighting system is considered. Costs for the proposed replacement system should account for reused equipment (e.g., most of the existing electrical wiring). Input values should reflect the combined performance and cost characteristics of the lamp/ballast/luminaire combination.

Section A

1. An estimate is prepared for material and labor of the installation. This amount is in dollars.
2. Enter the connected load of the lighting system, including ballasts and transformers, if any. This line should be in kilowatts.
3. Each lighting system introduces heat into the building, which must be dissipated by the air-conditioning system. One ton of air conditioning can dissipate the heat generated by 3.516 kW of lighting (equivalent to 12,000 Btu/h). If the lighting system choice alters the size of the air-condition-

ing equipment, the appropriate equipment sizes should be entered so that the difference in refrigeration tonnage is considered between alternate lighting conditions. If the air-conditioning equipment does not change, enter a zero on this line.

Note: If a daylighting system is being analyzed, the air conditioning loads are likely to be affected by the glazing conditions and by the interior and exterior shading devices employed.¹⁰

4. Enter the first cost of the air-conditioning equipment in line A3, which is between \$1000 and \$2000 per ton. Use the same value for each system. If the cooling requirements of the systems differ only by a few tons, the same nominal-size cooling plant can be used for both. For example, if one system requires 62 tons of cooling and another requires 64, then both designs might call for a 65-ton unit, and no first-cost differential would be realized. A similar caveat applies to item A5. The value on this line should be in dollars.
5. The heat generated by each lighting system can reduce the heating load on the building. This means that the heating plant can be smaller, and thus the first cost of the heating plant is reduced. Enter on line A5 the amount of that reduction for each lighting system as a negative number. Heating equipment costs range from approximately \$15 to \$25 for each kBtu it consumes. Each kilowatt of lighting reduces the heating needed by about 3.4 kBtu/h. This line should be in dollars. Note that in the analysis of a daylighting system, the effect on the cooling and heating loads should be addressed through a detailed analysis.¹¹
6. In order to reduce peak demand, electric utility companies in the United States may offer incentives for end users who retrofit or install energy-efficient lighting equipment in their buildings. Enter a financial incentive as a negative number, in dollars.
7. Include any other differential costs, such as insulation, solar power, or tax credits, in dollars.
8. The subtotal is the sum of lines A1, A4, A5, A6, and A7, taking proper note of signs.
9. Usually 6 to 8% of the first cost (line A8). Enter as a dollar amount.
10. The sum of lines A8 and A9.
11. The installed cost per square meter can be included as a memo; it does not enter into the LCCBA calculation.
12. The power density can be included as a memo; it does not enter into the LCCBA calculation.
13. The amount the system will be worth at the end of its economic life (as scrap, for example). Use the same life for each system under comparison. Note that this value is negative if money is received for the salvage; it is positive if a cost is incurred to

dispose of the system at the end of its life. This amount is in dollars.

Section B

1. The number of operating hours and cost per kilowatt-hour depends on occupancy schedules and local power rates. Ten hours a day, five days a week, 52 weeks per year represents 2600 h. In the United States, the average energy cost for commercial, institutional, and industrial customers is on the order of \$0.08 to \$0.09 per kWh. The impact of demand charges should be included in the kWh rate if the lighting system is expected to operate at the time of peak building demand. If the system is operated exclusively at off-peak hours, only the energy charge should be considered. This line is in dollars.
2. The number of tons of air conditioning should come from line A3. The number of kilowatts per ton for a central plant is approximately 1.25. The value in this line is in dollars.
3. This value can be approximated by \$150/ton times the air-conditioning tons from line A3, in dollars.
4. This is the reduction in the annual cost of fuel for heating equipment due to increased heat obtained from the lighting system. The number of heating hours can be obtained by the formula

$$\text{heating hours} = (\text{lighting hours}) \times 0.85 - (\text{cooling hours})$$

The heat from the lighting system in MBtu is given by this formula:

$$\begin{aligned} \text{heat from lighting system} &= (\text{kW of lighting}) \\ &\quad \times (3.413 \text{ MBtu/kWh}) \\ &\quad \times (\text{heating hours}) \end{aligned}$$

To convert costs of typical fuels to dollars per MBtu, multiply the cost of fuel (such as \$0.80/gal for fuel oil) by the corresponding value in column 4 of Figure 25-3 (such as 10 gal/MBtu). For example, if the price of electricity is \$0.10/kWh, the cost per MBtu is $(\$0.10/\text{kWh}) \times (293 \text{ kWh/MBtu}) = \$29.30/\text{MBtu}$. If the price of fuel oil is \$0.80/gal, the cost per MBtu is $(\$0.80/\text{gal}) \times (10 \text{ gal/MBtu}) = \$8.00/\text{MBtu}$. Thus

$$\begin{aligned} \text{annual reduction in heating energy costs} &= \\ &(\text{MBtu of heat from lighting}) \times (\text{fuel cost per MBtu}) \end{aligned}$$

This value should be in dollars. Note that if daylighting is used, the effects of shading devices on air-conditioning costs should also be considered.¹⁰

5. Heating maintenance costs can be approximated by \$2/MBtu. Multiply by the number of MBtu of heat from lighting to get a dollar amount.

Figure 25.3. Conversion Factors for Various Fuels

Fuel	Fuel Efficiency	Unit Energy	Fuel to obtain 1 MBtu
Electric heat	1.0	0.0034 MBtu / kWh	293 kWh
Coal	0.65	30 MBtu / ton	0.05 ton
No. 2 fuel oil	0.70	0.14 MBtu / gal	10 gal
Natural gas	0.70	1.0 MBtu / mCF	1.4 mCF / MBtu

6. Other costs may include costs, in dollars, for inspection of the lighting system.
7. The cost of lamps per year depends on the relamping strategy. If spot relamping is used, then the lamp cost per year is figured from this formula:

$$\text{lamp cost per year} = \frac{(\text{cost for spot replacement of one lamp}) \times (\text{number of lamps in the system})}{(\text{lamp life}) / (\text{annual burning hours})}$$

For group relamping, use

$$\text{lamp cost per year} = (\text{number of lamps replaced per year}) \times (\text{cost per lamp of group relamping})$$

Either way, the number on this line should be a dollar amount.

8. To annualize ballast costs, use

$$\text{ballast cost per year} = \frac{(\text{cost to replace one ballast}) \times (\text{number of ballasts in the system})}{(\text{ballast life}) / (\text{annual burning hours})}$$

This amount is in dollars.

9. Multiply the number of luminaires by the cost to clean a single luminaire to obtain the annual cost in dollars.
 10. Approximately 1 to 1.5% of first cost.
 11. Approximately 4 to 6% of first cost.
 12. The annual expenses of lines B1 through B11 serve to reduce the owner's income tax liability based on the income tax rate (ITR). The net cost of these items is entered as
- $$(B1 + B2 + B3 + B4 + B5 + B6 + B7 + B8 + B9 + B10 + B11) \times (1 - \text{ITR})$$
13. Depreciation reduces the owner's income tax liability. Assuming the asset is depreciated by the same amount each year (straight-line depreciation), the annual depreciation amount is given by

$$D = \frac{\text{initial cost from line A10}}{\text{economic life of system}}$$

If the owner's income tax rate (ITR) is expressed as a decimal fraction, then the tax effect is $T = D \times \text{ITR}$. This should be entered as a negative dollar amount, since it is a benefit or saving.

Section C

1. A present-worth comparison is done by finding "time zero" equivalents of all future costs and adding those to the initial costs of line A10. Equation 25-5 is used to convert the annual values in B12 and B13 to their equivalents at time zero. Use Equation 25-1 to convert the residual value (A13).
2. An annual-cost comparison requires that all one-time costs (initial costs and residual values) be converted to annual equivalents. These are then added to the annual energy and maintenance costs. Use Equation 25-6 to convert the initial cost of line A10 to its annual equivalent. The residual value (line A13) is converted to an annual value using Equation 25-7.

REFERENCES

1. Mangold, S. A. 1974. Lighting economics based on proper maintenance. *Light. Des. Appl.* 4(8):6-11.
2. Merrill, G. S. 1937. The economics of light production with incandescent lamps, with particular reference to operating voltage. *Trans. Illum. Eng. Soc.* 32(10):1077-1090.
3. Helms, R. N., and M. C. Belcher. 1991. Lighting economics. Chapter 14 in *Lighting for energy-efficient luminous environments*. Englewood Cliffs, NJ: Prentice Hall.
4. Belcher, M. C. 1989. Lighting cost analysis: Is there a better way? *Light. Des. Appl.* 19(6):14-21.
5. Belcher, M. C. 1989. MCSEALS: A Monte Carlo simulation for economic analysis of lighting systems. *J. Illum. Eng. Soc.* 18(2):40-51.
6. IES. Design Practice Committee. 1980. Life cycle cost analysis of electric lighting systems. *Light. Des. Appl.* 10(5):43-48.
7. Horngren, C. T., G. Foster, and S. Datar. 1996. *Cost accounting: A managerial emphasis*. 9th. ed. Englewood Cliffs, NJ: Prentice-Hall.
8. DeLaney, W. B. 1973. How much does a lighting system really cost? *Light. Des. Appl.* 3(1):22-28.
9. IES. Lighting Economics Committee. 1996. *Recommended practice for the economic analysis of lighting*, IES RP-31-1996. New York: Illuminating Engineering Society of North America.
10. IES. Daylighting Committee. 1979. *Recommended practice of daylighting*, IES RP-5-1979. New York: Illuminating Engineering Society of North America.
11. American Society of Heating, Refrigerating and Air-Conditioning Engineers. 1997. *ASHRAE Handbook: 1997 Fundamentals*. Atlanta, GA: ASHRAE.

Energy management has become increasingly important since the early 1970s, stimulated by the escalation of energy costs, the depletion of certain energy sources, and the concern for the protection of our environment. The responsible use of energy has become a general public concern and consequently has motivated development of new legislation, codes, and standards designed to establish minimum levels of energy efficiency. As a result, the way buildings are constructed, lighted, heated, and cooled is closely examined. Criteria for new building design and for existing buildings have been developed to ensure that energy resources are used efficiently. This chapter provides an overview of lighting energy management, describes important influences on lighting energy use, and provides references to other sections for more detail on specific lighting issues.

Electric lighting consumes a significant amount of energy. About 20 to 25% of all electricity used in buildings and about 5% of total energy consumption in the United States is used for lighting. Lighting also produces additional heat in buildings, which is sometimes beneficial in cold climates but generally represents a significant load on air conditioning systems. The heat from lighting typically accounts for 15 to 20% of a building's cooling load.

Over the last decade, energy management has become a fundamental element of mainstream lighting design. There have been many significant factors contributing to this trend. These factors include utility programs for promoting demand side management (DSM), the development and promulgation of energy codes and standards designed to minimize building energy waste, and ongoing technological development of lighting equipment to improve system efficacies and utilization efficiencies. This chapter provides an overview of current activity in all of these areas and shows how they relate to design and application issues.

LIGHTING SYSTEM DESIGN FOR ENERGY EFFICIENCY

The key elements of lighting design for energy efficiency are outlined schematically in Figure 26-1.

Lighting Needs

First and foremost, the lighting needs of a space must be defined to optimize proper allocation and management of energy. Lighting needs may range from simple orientation to

complex visual tasks. Important considerations for prolonged visual tasks associated with work environments include adequate illuminance on the task surface, a proper balance of luminance between the task surface and surrounding surfaces, control of direct and reflected glare, and acceptable color rendering of task elements and surrounds. Other considerations also apply, depending on the details of the specific visual task being performed.

When the nature and location of visual tasks can be identified, it is usually possible to reduce surrounding ambient illuminances and corresponding energy consumption by providing light more selectively where and when it is needed. When specific tasks and their locations cannot be identified, a more uniform pattern of ambient illumination is generally provided, along with provisions for task lighting and local control. In applications where there are no prolonged visual tasks, lighting for emphasis, aesthetics, and safety are prime considerations.

Lighting needs for specific applications can be found in Chapter 10, Quality of the Visual Environment, and the relevant application chapters. In addition, there are numerous IESNA publications that provide guidance in identifying and addressing lighting needs.¹⁻³ The ASHRAE/IESNA Standard 90.1⁴ and its compliance manual can be consulted for guidelines in determining lighting energy allocations for specific applications.

Space Design and Utilization. Space design and utilization characteristics are often determined before the lighting system is considered. However, it is necessary to coordinate the design of lighting and control systems with these characteristics in order to maximize the energy efficiency potential. For larger interior spaces, surface reflectances should be 0.7 or higher. This increases the brightness within the space and reduces the amount of electric lighting needed to produce a given illuminance. The design and utilization of a space should also facilitate effective use of daylight.

Applications that involve similar visual tasks should be grouped together when possible to optimize the energy used for lighting. Using a base level of ambient illumination with "layers" of task-specific luminaires provides an additional degree of flexibility and economy by allowing luminaires to be easily relocated when the design or function of a space changes.

Occupancy schedules of a space should be planned to optimize the effectiveness of lighting controls. Traffic patterns should be predetermined so that logical applications for oc-

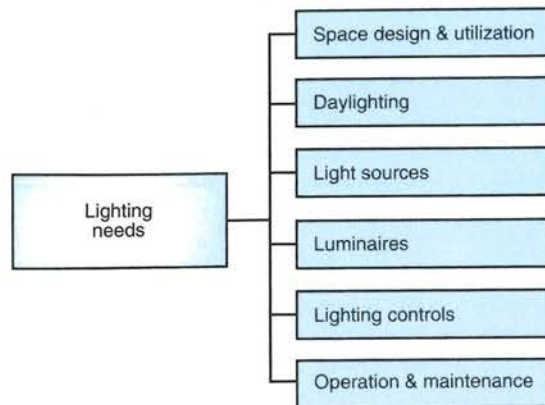


Figure 26-1. Key elements of lighting energy management.

cupancy sensors can be identified. This usually requires coordination among members of the project design team.

Daylighting. Daylight can be an excellent source of ambient illumination. The potential for daylight utilization should be evaluated early in the design development of a space. Architectural features such as overhangs, light shelves, and window treatments may be incorporated into the design to enhance daylight utilization and control. For effective use of daylight in energy management, the levels and hours of daylight availability must be determined. Also, the manner in which daylight is distributed in the space is important. Glare from fenestration should be controlled to the same degree as glare from luminaires (Figure 26-2). The best daylighting designs maximize daylight penetration into the space while minimizing the negative effects of direct sun.

The heat gain or loss through fenestration must be coordinated with the building envelope and HVAC systems. The use of exterior sun control devices and high-performance heat-reflecting and insulating glass in windows should also be considered to minimize solar heat gain in the summer and heat loss in the winter without obstructing views of the exterior. Daylighting reduces energy consumption primarily if electric lighting can be reduced. The electric lighting design should be coordinated with available daylight so that illuminance and distribution are integrated. Automatic and manual dimming controls should be considered for continuous adjustment of electric lighting levels to achieve maximum energy savings and occupant acceptance.^{5,6}

Chapter 8, Daylighting, can provide useful information on the availability of daylight, daylight control systems, and design and evaluation methods. Recently published data from manufacturers of fenestration materials and controls should also be consulted.

Light Sources. Electric light sources should be selected to maintain the highest efficacy while providing proper color qualities, physical and optical size, and long-life operating



Figure 26-2. Effective utilization of daylight is important. Glare from fenestration should be controlled to the same degree as glare from luminaires.

characteristics (e.g., warm-up time, restrike time, and dimming). These attributes are related to decisions on luminaire types, lighting controls, and the general operation and maintenance after installation.

The relative efficacy ranges of commonly used light sources, including ballast losses, are shown in Figure 26-3. Within a lamp type, the higher-wattage sources are generally more efficacious than the lower-wattage sources. High-pressure sodium, metal halide, and fluorescent lamps are the most efficient white light sources; mercury vapor and standard incandescent lamps are the least efficacious. Except for incandescent lamps, including halogen lamps, light sources require a specific ballast. Ballast efficiencies vary and can have a large effect on the total lighting system efficacy. Also, fluorescent lamp electronic ballasts are more efficient than magnetic ballasts and generally improve lighting quality by reducing lamp flicker and ballast hum.

There are other key issues that must be considered when selecting a ballast. One of these is ballast factor, which rep-

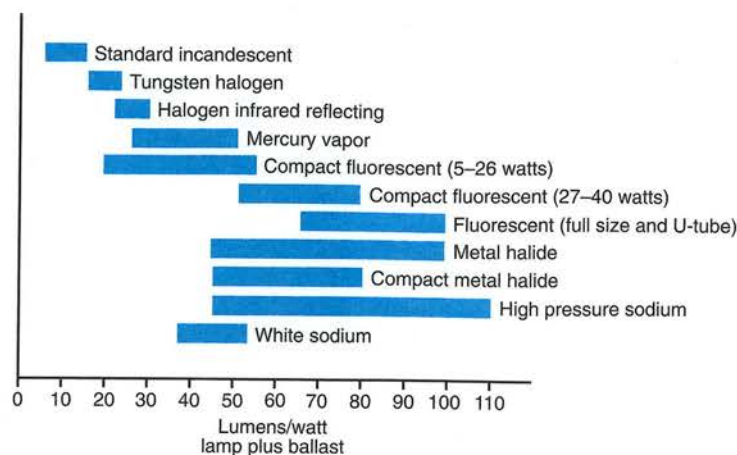


Figure 26-3. Light source efficacies.

resents the percentage of rated lamp lumens that is produced by a ballast relative to those produced by a reference ballast. Low-output ballasts have a low ballast factor and require proportionally lower power. A method for comparing the efficacy of lamp/ballast systems on a normalized basis is the calculation of Ballast Efficacy Factor (BEF). BEF is defined as ballast factor (BF) in percent, divided by the total ballast input power in watts.⁷

$$BEF = \frac{BF \times 100}{\text{ballast input watts}}$$

A higher BEF value indicates a more efficacious lamp-ballast system. Since BEF is a comparative expression for a given lamp-ballast combination, only two-lamp ballast systems should be compared with each other, three-lamp ballast systems with each other, and so on. See the section "Equip-

ment Regulations" later in this chapter for U.S. regulation of BEF. Also, see Chapter 6, Light Sources, for more information about ballasts.

Chapter 6, Light Sources, provides detailed information pertaining to the operation and performance of various lamp types. Lamp manufacturers' published data provide specific information relative to lumen output, efficacy, life expectancy, lumen maintenance, and costs.

Luminaires. A luminaire is an assembly of individual components including lamps, ballasts, sockets, wiring, and optical media such as reflectors, louvers, and lenses. The efficiency of the luminaire is affected by the performance of these individual components. Typically, luminaire configurations are constructed to perform specific functions for specific applications (Figure 26-4). Application constraints such as ambient temperature, color requirements, accessibil-

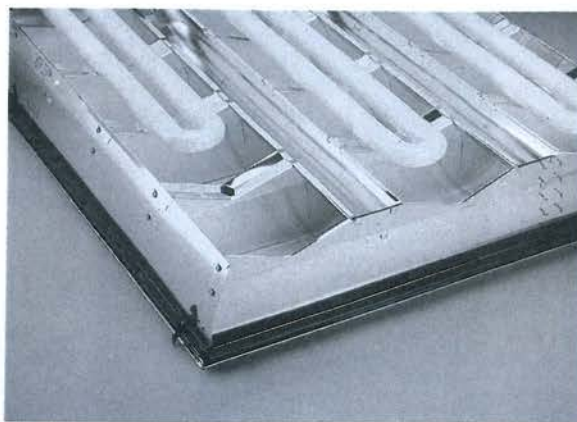


Figure 26-4. The performance of luminaires is a function of source efficacy, geometry (downlight vs. linear luminaire), the optical system for controlling distribution and shielding, and the ability of the luminaire to manage and dissipate heat created by components.

ity, and glare control needs may require the use of certain components or preclude the use of others. The efficiency of a luminaire must be evaluated relative to specific application criteria.

In spaces that contain important visual tasks, a primary objective of the lighting system is to illuminate the task effectively. In addition, the system must effectively illuminate the ambient space to balance luminances and create a comfortable visual environment. The system that provides task illuminance may be independent of the system that provides ambient illuminance, or else the same system may provide both (Figure 26-5). In either case, it is important that the luminaires perform their functions efficiently and that the designer understand their optical performance and impact on the overall environment.

Luminaires that can be cleaned easily and those with low dirt accumulation maintain greater efficiency and reduce maintenance costs over system life. When possible, luminaires with heat-transfer capabilities should be considered for interior applications so that heat generated by the lighting system can be effectively utilized or removed from a space and coordinated with the overall building HVAC design.

Data from luminaire manufacturers are useful for determining how efficiently luminaires meet lighting needs. The efficiency of a luminaire is the percentage of lamp lumens produced that actually exits the luminaire. Efficiency does not provide any indication of lighting quality and should not be the determining factor in luminaire selection. Chapter 7, Luminaires, should be consulted for further information about luminaires.



Figure 26-5. An ambient lighting system that also provides wall and task lighting.

Lighting Controls. The most efficient luminaires and light sources can be utilized even more effectively by integrating them with lighting controls that make the lighting more responsive to changing requirements. Lighting control strategies should be implemented either centrally, over an entire building, or locally, in individual areas. Various combinations of these two levels of control are also common.

Central lighting control systems allow for lighting load scheduling to reduce peak demand as well as provide the ability to monitor and control total energy use. Central lighting control systems can be interfaced with overall building management systems (BMS). Most energy codes require that a discrete space be provided with some means of controlling the lighting within that space (Figure 26-6).

A building also can be divided into areas that have different lighting needs and require different control strategies. For example, perimeter zones consisting mainly of private offices should be differentiated from core zones utilizing an open-plan landscape. Private offices are good candidates for manual and automatic lighting control because they have unpredictable occupancy schedules, they are typically low-traffic areas requiring task-level illumination only when occupied, and they often utilize a significant daylight contribution.⁵

Lighting control strategies are closely related to space utilization. It is essential to understand and coordinate space utilization in order to optimize the effectiveness of lighting controls for energy management (refer to the section "Space Design and Utilization" above). Lighting controls must eliminate or reduce lighting during off hours. The system must be flexible so that luminaires are used only where and when the relatively few people working late at night or on weekends are present. Off-hours operation should not defeat shut-off controls and thereby allow lighting to operate all night or all weekend.

Chapter 27, Lighting Controls, should be consulted for a more detailed discussion of lighting controls. Information

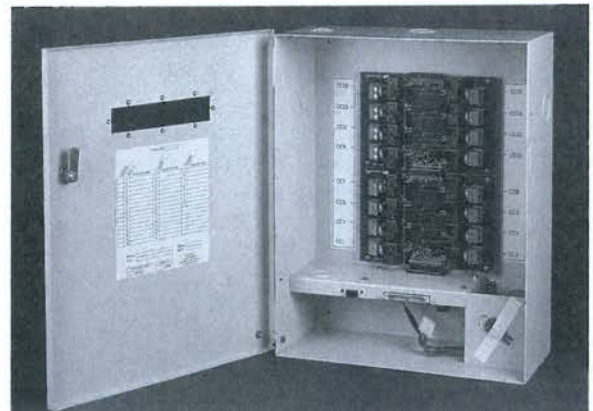


Figure 26-6. An example of a central lighting control system based on programmable time-of-day operation of relays and low-voltage switching.

from manufacturers should also be consulted for performance data and application assistance on various control technologies.

Operation and Maintenance. All lighting systems require maintenance after installation. A planned maintenance program augments the ability of a lighting system to meet design objectives effectively and efficiently throughout its life. Scheduled maintenance should include procedures for lamps, ballasts, luminaires, controls, fenestration, and room surfaces. Group relamping and a regular cleaning program are recommended for maximum maintained efficiency.

A planned systematic maintenance schedule saves energy and operating costs over time. If the commitment to implement scheduled maintenance is made in the initial stage of design, a significant capital cost saving is also possible because less equipment is required. Refer to Chapter 28, Lighting Maintenance, for a more detailed discussion relative to efficient operation and maintenance of lighting systems.

ENERGY EFFICIENCY FOR EXISTING BUILDINGS

Existing buildings should comply with the same lighting energy recommendations as new buildings. Improved energy utilization options include modifying or replacing lighting systems, using reduced-wattage sources in spaces that provide higher illuminance than currently recommended, and modifying the operating hours of the lighting equipment.

Specifying lighting system changes for existing spaces can be more accurate than it is for new construction because the space and its use can be surveyed. An existing building is evaluated from the standpoint of power and energy by two methods: a building survey and the determination of the lighting power allowances.

Building Survey

A building's lighting systems can be assessed to determine the existing lighting condition, current lighting needs, the connected electrical load, hours of operation, and the controls system. The electrical load, including lamp watts, ballast watts, and losses (including those introduced by dimming devices), should be documented. The power for portable and supplementary lighting devices should be included in the total. Factors related to occupancy, daylighting, and controls should be included. Specific information on surface finishes and reflectances should also be recorded. Sampling procedures can be used to avoid measuring every feature of the space.

Lighting Power Allowance Determination

Local energy codes and ASHRAE/IESNA 90.1-1999 provide the total lighting power allowance (TLPA), which con-

sists of exterior lighting power allowance (ELPA) and interior lighting power allowance (ILPA), as well as procedures for calculating them and control requirements for interior and exterior illumination systems.⁴

The actual current energy use for the facility is determined and compared with the energy limit. The difference is the energy saving from the retrofits. The resulting revised energy use estimate can be compared with the recommended energy limit. If it exceeds the limit, the lighting systems should be reevaluated. Spaces or strategies that are inefficient should be identified and modified to reduce the estimated energy below the calculated limit. Reference 8 contains the full procedure and energy management forms to estimate and evaluate lighting energy use for buildings.

LIGHTING EFFICIENCY STANDARDS, REGULATIONS, CODES

Lighting efficiency standards are designed to establish maximum energy levels for a building. The overall goal is to minimize energy consumed by a lighting system without compromising the quality of the lighting design. Generally, one of two approaches is taken: setting minimum efficiency for specific components or limiting the available power for lighting. The latter approach is commonly known as an application standard, whereas the former is known as equipment regulations. Over the last decade, both application standards and equipment regulations have been enacted into building energy codes by federal, state, and provincial governments in North America. Both of these approaches address lighting power, but it should be remembered that energy savings (kilowatt-hours) can be achieved by reducing the connected load power for the lighting system or the time the lighting system is operated.

Applications Standards/Codes

Lighting application standards can encourage good lighting principles and do not prescribe the use of specific technologies, because inexpensive equipment is not necessarily the most energy efficient or cost effective. Life-cycle cost models are very effective for justifying the economic merits of increased equipment efficiency (see Chapter 25, Lighting Economics).

Current ASHRAE/IESNA Standards. The industry benchmark of energy application standards for buildings is the ASHRAE/IESNA series. As a combined effort of the Illuminating Engineering Society of North America (IESNA) and the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), the first building energy standard was published in 1975. This standard, 90.1: "Energy Conservation in New Building Design," was developed as a national voluntary consensus standard. The 1980 version of this standard was approved as an ANSI standard.

During the 1980s, many states and provinces in North America enacted regulations based directly or indirectly on this standard. The standard has been updated three times; the current version is ASHRAE/IESNA 90.1-1999 Energy Standard for Buildings Except Low-Rise Residential Buildings.⁴

The purposes of the standard are to:

- Set minimum requirements for the energy-efficient design of new buildings so that they may be constructed, operated, and maintained in a manner that minimizes the use of energy without constraining the building function or the comfort or productivity of the occupants.
- Provide criteria for energy-efficient design and methods for determining compliance with these criteria.
- Provide sound guidance for energy-efficient design.

The organization of ASHRAE/IESNA 90.1-1999 is shown in Figure 26-7. All buildings must meet the basic requirements. The basic requirements with respect to lighting, relative to the above purposes, include minimum criteria for lighting controls, power allowance for internal building lighting, and power allowance for external building lighting. For internal building power allowances, Standard 90.1 offers a choice of three different methods for determining compliance: energy cost budget, prescriptive path for a building

(Building-Area Method) or prescriptive path for spaces in a building (Space-by-Space Method).

The energy cost budget approach is the most encompassing and complex method of assessing compliance. A whole-building energy model must be used to predict energy use. It allows the designer to trade off lighting energy with other energy systems (e.g., the HVAC system). Although the method is flexible, it requires sophisticated analysis tools and is time consuming.

The Building Area Method addresses the need for a quick and simple process for calculating the prescriptive interior lighting power allowance (ILPA) for whole building types. This method does not address unique project requirements and is intended primarily for generic building types, core and shell buildings, or during the preliminary design phase. The ILPA is calculated by selecting the lighting power density from a table in the standard, multiplied by the gross lighted floor area (square feet or square meters) of the building. The actual design is measured against the value determined with this method.

The Space-by-Space Method provides a more accurate and detailed calculation procedure to determine the ILPA than the prescriptive method. The ILPA is calculated room by room and is task specific. Lighting power densities for each space are listed in a table in the standard. The ILPA for the building is the sum of lighting power allowances of all spaces. Similarly, the exterior lighting power allowance is

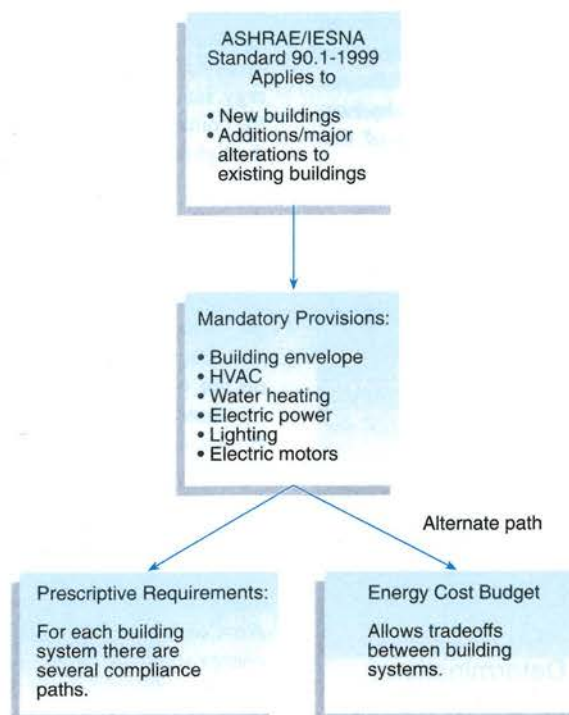


Figure 26-7. The structure of ASHRAE / IES Standard 90.1-1999.

the sum of lighting power allowances for all applicable exterior applications permitted.

While ASHRAE/IESNA 90.1-1999⁴ applies to new buildings, ASHRAE/IESNA Standard 100⁹ applies to existing buildings. It provides requirements for retrofit lighting modifications. In general, the required changes can be done easily by maintenance personnel. When major renovations are made to existing buildings, for example, when the entire lighting system is replaced, it is recommended that the designer meet the requirements for new construction even though compliance may not be required.

Compliance with Standard 90.1-1999⁴ or Standard 100⁹ does not ensure good lighting. The purpose of these standards is to set limits on the amount of power that can be used for lighting. While it is the consensus of experts that good lighting can be achieved within the limits set by Standard 90.1, it is the responsibility of the designer to achieve it.

U.S. State Energy Codes. State legislation governing lighting energy consumption varies from state to state. The federal Energy Policy Act of 1992 (EPACT),¹⁰ requires all states to adopt a building energy code that meets or exceeds the requirements of ASHRAE/IES 90.1-1989. The Model Energy Code (MEC)¹¹ contains a codified version of Standard 90.1-1989 and is used by many states to meet the EPACT requirement. The MEC has been developed by the Council of American Building Officials (CABO) with participation of other building code officials.

Canadian Application Standards/Codes. The Canadian Standing Committee on Energy Conservation in Buildings (a subcommittee of the Canadian Commission on Buildings and Fire Codes) is in the process of developing a National Energy Code for commercial buildings and for homes. Once finalized, the regulation of buildings in Canada will be the responsibility of provincial and territorial governments. Provinces will have the option of adopting all or part of the National Energy Code.

Mexican Energy Codes. Mexico has no formal energy standards or code requirements at the state or federal level.

Equipment Regulations

In both the United States and Canada, the government has been playing an increasing role in regulating the conservation of lighting energy through standards on lighting components. The primary institutions responsible for national standards are the U.S. Department of Energy (DOE) and Natural Resources Canada (NRC). Harmonization of standards is necessary so that (1) lower efficiency products are not dumped from a country with regulations to one without, (2) manufacturers can design products according to one standard instead of several, and (3) the regulatory burden is decreased.

U.S. Regulations. Two laws specifically mandate the use of efficient lighting components: the National Appliance Energy Conservation Amendments of 1988 (NAECA)¹² and the

Energy Policy Act of 1992 (EPACT).¹⁰ NAECA regulates the sale of inefficient ballasts for fluorescent lamps. Ballasts sold for use in commercial or industrial lighting installations were required to meet or exceed minimum BEF values, discussed earlier in this chapter.

The impact of this regulation was that common magnetic ballasts did not comply, but more energy-efficient magnetic ballasts and efficient electronic ballast did. The law exempted dimming ballasts and those for use at ambient temperatures of -18°C (0°F) or less, and ballasts with low power factor (less than 0.90) for residential use. Ballasts that meet the efficiency criteria are identified by a circle E symbol on the label (Figure 26-8).

EPACT mandated energy-efficiency standards for common lamps used in the United States. Minimum efficacy standards were developed for popular lamp types within the categories of incandescent R and PAR and linear fluorescent lamps (see Figures 26-9, 26-10, and 26-11 and Chapter 6, Light Sources). These standards were phased in during 1994 and 1995. The impact was that halogen PAR lamps complied, whereas the standard and reduced-wattage PAR lamps and many R lamps did not. For 4-foot and 2-foot U-tube, 8-foot slimline, and 8-foot high-output fluorescent lamps, the



Indicates ballast complies with National Energy Conservation Amendments (NAECA) of 1988 to Energy Policy and Conservation Act (EPCA) of 1987.

Figure 26-8. "Circle E" symbol that appears on fluorescent lamps and ballasts.

Figure 26-9. U.S. Minimum Allowable Ballast Efficacy Factors

Ballast-Lamp System	Nominal Lamp Watts	Ballast Efficacy Factor
1 F40T12	40	1.805
2 F40T12	80	1.06/1.05
2 F96T12	150	0.570
2 F96T12HO	220	0.390

Note: BEFs apply to ballast designed for an input of 120 V or 277 V. For 2-lamp F40T12, the two BEFs listed are for 120/277 V.

Figure 26-10. U.S. EPACT Incandescent Reflector Lamp Standard Levels

National Lamp Wattage	Minimum Average Lamp Efficacy (lumens/Watt)
40–50	10.5
51–66	11.0
67–85	12.5
86–115	14.0
116–155	14.5
156–205	15.0

Figure 26-11. U.S. EPACT Fluorescent Lamp Standard Levels

Lamp Type	Nominal Lamp Wattage	Minimum CRI	Minimum Average Lamp Efficacy (lumens/Watt)
4-foot medium bi-pin	> 35 W	69	75.0
	35 W	45	75.0
2-foot U-shaped	> 35 W	69	68.0
	35 W	45	64.0
8-foot slimline	65 W	69	80.0
	65 W	45	80.0
8-foot high output	> 100 W	69	80.0
	100 W	45	80.0

standard established minimum requirements for both efficacy and color rendering index (CRI). Effectively, reduced-wattage T-12 halophosphor fluorescent lamps complied, as did T-8 and T-12 fluorescent lamps coated with rare earth phosphors. Common fluorescent lamps with halophosphor coatings did not comply. EPACT also called for test procedures, standards, and labels for HID lamps where standards are technically feasible and economically justified and offer significant energy savings potential.

EPACT prescribed an energy-efficiency labeling program for common general-service incandescent and fluorescent lamps, incandescent reflector lamps, and medium-base self-ballasted screw-in compact fluorescent lamps sold or imported in the United States. This program was designed by the Federal Trade Commission (FTC) and took effect in 1995. The FTC lamp labeling procedure for incandescent and compact fluorescent lamps required that lamp packages display lumen output, lamp wattage, rated lamp life, and design voltage (if other than 120 V). Full-size fluorescent lamps are not required to have package labels. Instead, the circle E symbol must be etched on the lamp itself, indicating that the lamp meets the EPACT lamp efficacy requirements described above (Figure 26-8).

EPACT called for a voluntary national testing and information program for widely used luminaires that offer potential for significant energy savings. The program was designed by the National Lighting Collaborative, composed of NEMA (National Electrical Manufacturers Association), the American Lighting Association (ALA), and other interested organizations representing lighting designers, energy-efficiency advocates, research, government, and electric utilities.

The luminaire program was based on a rating methodology, developed as NEMA Standard LE-5, called the Luminaire Efficacy Rating (LER).¹³ LER is defined as the ratio of the total luminaire lumens (incorporating ballast factor and thermal effects) to the system input wattage. It includes the efficiency impact of each system component: fixture, lamp, and ballast. LER is expressed by the following formula:

LER =

$$\frac{\text{total rated lamp lumens} \times \text{ballast factor} \times \text{luminaire efficiency}}{\text{luminaire input watts}}$$

The fluorescent lamp luminaire program covers eleven categories of commonly used luminaires representing a large majority of the fluorescent lamp luminaire market. For each luminaire, the LER rating is reported along with a code for its luminaire category so that products can be compared fairly within categories (rather than between categories). The rating is designed with a placeholder for the addition of an as yet undeveloped quality metric to indicate lighting quality. The estimated annual lighting energy cost per 1000 lumens of light output, assuming 3000 operating hours per year and \$0.08 (U.S.) per kWh electricity cost, is also reported.

Canadian Standards. Natural Resources Canada has regulatory powers under the Energy Efficiency Act of 1993.¹⁴ The first Energy Efficiency Regulations were published in 1994. NRC works with the Canadian Standards Association (CSA), which develops consensus standards for various products. National standards apply to products imported into Canada or shipped between provinces. The provinces may adopt these standards for products sold within their borders. Federal standards do not take precedence over provincial standards, in contrast with the United States, where federal standards preempt state standards on a specific product.

The first lighting product included in the Energy Efficiency Regulations was fluorescent lamp ballasts. As of 1995, ballasts must meet the minimum ballast efficacy factors specified in the CSA standard.¹⁵ These standards are similar to those listed above for the United States, with the exceptions that F32T8 lamp ballasts are also regulated and that there are standards for ballasts with an input of 347 volts as well as 120 and 277 volts (Figure 26-12).

Canadian lamp regulations are the same as the U.S. EPACT standards for incandescent reflector and linear fluorescent lamps. These standards took effect in 1996.

There are no lamp labeling requirements in Canada similar to those in the EPACT legislation. However, regulated lighting products must carry a verification mark indicating that the energy performance of the product has been verified.

Figure 26-12. Canadian Minimum Allowable Ballast Efficacy Factors

Ballast-Lamp System	Nominal Lamp Watts	Ballast Efficacy Factor
1 F40T12	40	1.805/1.805/1.750
2 F40T12	80	1.060/1.050/1.020
2 F96T12	150	0.570/0.570/0.560
2 F96T12HO	220	0.390/0.390/0.380
2 F32T8	64	1.250/1.250/1.200

The provinces Ontario, British Columbia, Quebec, Nova Scotia, and New Brunswick have standards similar to the federal regulations for fluorescent lamp ballasts. Ontario and British Columbia have also implemented standards for incandescent reflector lamps and are looking at adopting the standards for fluorescent lamps. In addition, Ontario and British Columbia have regulated compact fluorescent lamps and cobra-head HID luminaires based on recently published CSA standards for compact fluorescent lamps and roadway lighting.

Nonregulatory Government Programs

Government agencies also promote energy efficiency and energy conservation through voluntary programs. The Green Lights Program and Energy Star Building Program are administered by the U.S. Environmental Protection Agency (EPA). These programs are voluntary initiatives designed to reduce building energy load on a national scale.

The objective of the Green Lights Program is to minimize pollution associated with the generation of energy required to operate new and existing lighting systems. Large and small companies and institutions have committed to survey lighting systems in their facilities and convert to energy-efficient lighting when economically viable. For new installations, the recommendations of ASHRAE/IESNA Standard 90.1-1999⁴ are to be followed.

The ENERGY STAR Program is a more comprehensive building initiative that encourages use of energy-efficient technologies for all major building systems, including lighting. A partnership agreement is signed between a luminaire manufacturer and EPA and the U.S. Department of Energy (DOE). EPA and DOE work with the luminaire manufacturer to promote superior products that qualify for the EPA/DOE ENERGY STAR label. Products that carry the ENERGY STAR label meet energy efficiency and quality criteria to assure that consumers do not sacrifice performance to save energy. The Lighting Research Center (LRC) in Troy, New York, helps EPA and DOE promote the ENERGY STAR Program by encouraging manufacturers to participate in the program; by testing energy-efficient products and drafting performance specification for labeling programs, specifiers, and procurement groups; and by disseminating information through publications such as *Specifier Reports* and *Lighting Futures*.

REFERENCES

1. IESNA. Standard Practice Subcommittee of the Office Lighting Committee. 1993. *American national standard practice for office lighting*, ANSI/IESNA RP-1-1993. New York: Illuminating Engineering Society of North America.
2. IESNA. Committee on Industrial Lighting. *American national standard practice for industrial lighting*, ANSI/IES-RP-7-1991. New York: Illuminating Engineering Society of North America.
3. The IES *Recommended Practice for Lighting Merchandising Areas*, IES RP-2-1985 is under revision. Expected publication date is Spring 2000.
4. American Society of Heating, Refrigeration and Air-Conditioning Engineers and Illuminating Engineering Society of North America. 1999. *Energy standard for buildings except low-rise residential buildings*, ASHRAE/IESNA 90.1-1999. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.
5. Maniccia, D., B. Rutledge, M. Rea, and N. Narendran. 1998. *A field study of lighting controls*, Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.
6. National Lighting Product Information Program. 1998. *Specifier reports: Photosensors*, Troy, NY: Rensselaer Polytechnic Institute.
7. Ji, Y. 1997. *Specifier reports supplements: Electronic ballasts*, Troy, NY: Rensselaer Polytechnic Institute.
8. IES. *Design Consideration for Effective Building Lighting Energy Utilization*. IES LEM-3-1987.
9. American Society of Heating, Refrigeration and Air-Conditioning Engineers. 1995. *Energy conservation in existing buildings*. ASHRAE 100-1995. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.
10. *Energy Policy Act of 1992*. U. S. Public Law 486, 102nd Cong. 24 October 1992.
11. Building Officials Code Administration. 1998. *International Energy Conservation Code*. Country Club Hills, IL: BOCA.
12. *National appliance energy conservation amendments of 1988*. U. S. Public Law 357, 100th Cong. 28 June 1988.
13. National Electrical Manufacturers Association. 1993. *Procedure for determining luminaire efficacy ratings for fluorescent luminaires*, NEMA LE 5-1933 Rev. 1995. Washington, D.C.: National Electrical Manufacturers Association.
14. Canada. *Statutes of Canada*. 1992. E6.4, c.36.
15. Canadian Standards Association. 1997. Fluorescent lamp ballast efficacy measurements, CSA-C654. Etobicoke, ON: CSA.

The lighting controls covered in this chapter are electronic controls for electric lighting. Generally light sources are equipped with these controls for one of two reasons: for aesthetic control, which matches lighting intensity to the application and therefore controls the quality of the visual environment, or for energy management control, which limits the application of light to times when there is a demand and therefore reduces unnecessary lighting energy.

Proper use of these controls can assist with compliance with ASHRAE/IESNA 90.1 and the Canadian national energy code guidelines, reduce building operating costs, and significantly benefit the environment. It is incumbent on the engineer and lighting designer to be aware of the wide variety of electronic lighting controls available and to correctly apply them to the project at hand. As in all technology-driven areas, investigation of the current state of the art must be completed periodically in order to stay current in the field.

In the past, controls were used primarily to turn lights on or off, or for special purposes such as stage, theater, and conference room lighting. More recently the use of controls has become an essential element of good lighting design and an integral part of energy management programs for lighting of commercial, residential, industrial, and exterior areas. Lighting controls for specific applications are described in the various application chapters of this Handbook.

A variety of strategies and techniques has been developed to control a building's power demand, energy consumption, lighting equipment, and working environment. Some equipment is best suited for new construction and renovation, whereas other equipment is better suited for retrofit. This section describes different types of lighting control strategies, techniques, and equipment and their effects on building systems and occupants.

Studies of buildings that have implemented control strategies have shown that it is possible to reduce overall lighting energy consumption by as much as 80% in some localities.^{1,2} Cumulative savings are dependent on the building configuration, the control hardware specified, the combination of control strategies selected, and the extent to which each of the control strategies is available for use within a building.

LIGHTING CONTROL STRATEGIES

There are three major objectives for the use of lighting controls: energy management, aesthetics, and code compliance

measures. Energy management controls for lighting systems provide energy and cost savings through reduced power or reduced time of use. Aesthetic controls provide the ability to change space functions and can create emotional appeal, offering control of lighting quality, mood, color, and attitude. These benefits are not necessarily in conflict. Energy management control strategies can significantly improve the quality of a space, and controls installed primarily for aesthetic purposes can produce significant energy savings. Here, however, the two benefits are discussed separately. Power density credits are often given for control systems, enabling additional lighting to be used in a space, or to reduce overall energy consumption to meet code objectives.

Energy Management Strategies^{3,4}

Predictable Scheduling. Where activities in a building occur routinely during the day, luminaires throughout the space can be operated on a fixed schedule (with overrides in case there are variations in the schedule). For example, staff arrival and departure times, lunch periods, and cleaning hours are predictable for weekdays, weekends, and holidays in many manufacturing plants, offices, schools, libraries, and retail stores.

Predictable scheduling strategies are particularly effective when work schedules are well defined for the entire area. Such strategies can reduce energy by as much as 40% by eliminating energy waste caused by lights operating in unoccupied spaces. Automatic scheduling also relieves staff of the burden of operating lighting controls and can be used to signal times of particular activities, such as the opening and closing of retail stores. It is unacceptable, however, to plunge occupants into darkness when scheduling the operation of the lighting system, so some provision for overriding the schedule should be provided.

Unpredictable Scheduling. Many events are unpredictable and unscheduled, such as workstation vacancies due to sickness, vacations, staff meetings, and business trips. Unassigned areas such as restrooms, copy centers, filing areas, conference rooms, break rooms, and retail store dressing rooms are used sporadically and are not readily scheduled. Though these areas may not be amenable to tightly scheduled lighting operation, local automatic control techniques can be more cost-effective than the usual reliance on manual operation of lights. Unpredictable scheduling strategies using occupancy/motion sensors have yielded energy savings

of over 60% in some areas. To assess the benefits of automatic controls, it is important first to determine the proportion of time the space is vacant. It is also important to consider that switching lights on and off can disturb occupants of adjacent spaces, as in an open-plan office. For reasons of aesthetics, safety, and user acceptance, lights in these spaces can be dimmed rather than switched off completely. Today occupancy sensors are being used to control lighting, HVAC, and office equipment (e.g., computer monitors) in offices, warehouses, library stacks, and many other areas.

Daylighting.⁵⁻⁸ In the perimeter areas of buildings, part of the desired illumination can often be supplied by daylight (see Figure 27-1 and Chapter 8, Daylighting). In these areas, reducing the power for electric lighting in response to the amount of available daylight reduces energy consumption.

Both dimming and switching strategies can be used. For successful application of daylight-based switching, high levels of daylight must be present so that sufficient illumination for the task remains after the electric lighting has been lowered (Figure 27-2).

The energy savings realized from daylighting depends on many factors, such as the climatic conditions; the building form, orientation, and design; the sensor and control design and installation; and the activities within the building. Under some conditions, daylight can reduce electric energy costs significantly when photoelectric sensor controls are used. This is particularly important during peak power demand hours when the cost of electric energy can be much higher than during off-peak hours. It is essential that control of the electric lighting be properly integrated with the daylight illumination pattern to maintain adequate quantity and quality of lighting.

With respect to photosensor controls, the size and shape of control zones are usually constrained by the rapid falloff of horizontal illuminance from the window wall. Although lighting zones can be laid out to cover a single task area, a

room, or an entire building, in practice the lighting zones should be close to the daylight-admitting elements. For typical spaces illuminated by daylight from a side window, the lighting zones should be adjacent to the window wall and no more than 4 m (13 ft) deep. The row of luminaires nearest the window should be controlled on a separate circuit from those in the interior area. Occupancy sensors manufactured today can have daylight sensing as a feature. If manually operated window shading devices are used, smaller control zones may be required for daylighting to be effective.

Brightness Balance. Lighting design often dictates limits to the brightness within or among spaces. (See Chapter 3, Vision and Perception, and Chapter 10, Quality of the Visual Environment). One design goal is to balance different brightness levels so that glare and shadows are reduced. For example, lighting controls can be used to mitigate the very high brightness produced by windows in interior spaces. One control technique is to limit light entering the space with blinds or louvers. Another possibly counterintuitive approach for interior spaces is to increase the illuminance produced by the electric lights. Often controls can be used to provide a luminous transition between two spaces having very different brightness levels. Perhaps the most common example is tunnel lighting (see Chapter 22, Roadway Lighting). The illuminance produced by the electric lights in the entry zone of the tunnel depends on the level of daylight illuminance; higher illuminances are produced by the electric lights in this zone on sunny days than on cloudy days.

Lumen Maintenance. Lighting systems are usually designed for a minimum maintained illuminance level. This requires the level of a new lighting system to exceed the design minimum by 20 to 35% to allow for lumen depreciation, specifically lamp lumen depreciation, luminaire dirt depreciation, and room surface dirt depreciation (see Chapter 9, Lighting Calculations and Chapter 26, Energy Man-

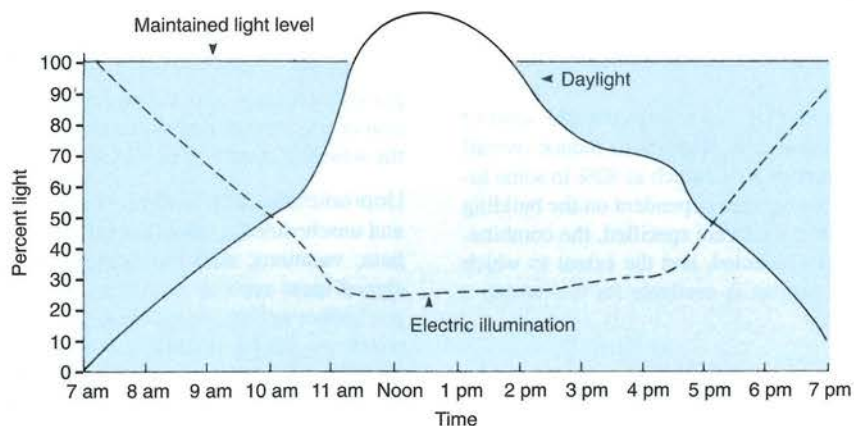


Figure 27-1. Photocell-activated dimmers maintain a constant light level by adjusting the output of electric illumination according to changing ambient illuminance.

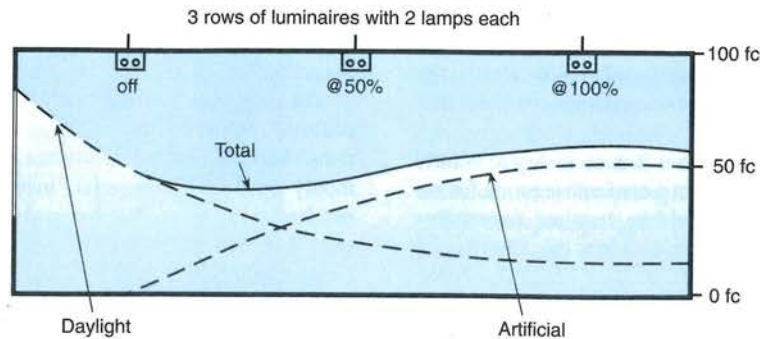


Figure 27-2. Illustration showing the rapid drop-off of illuminance from the window wall. In this space, daylight must be supplemented by electric lighting as the distance from the window wall increases.

agement). Lumen depreciation control strategy calls for reducing the initial illumination of a new system to the designed minimum level. As lumen depreciation occurs, more power is applied to the lamps in order to maintain constant output. Thus, full power is applied only near the end of the lumen maintenance period, significantly reducing energy use over the life of the lamp (Figure 27-3).²

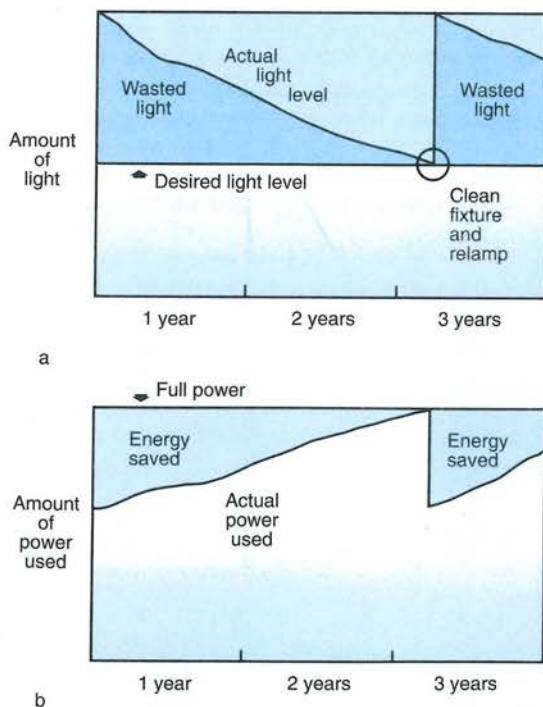


Figure 27-3. Lumen maintenance control strategy. (a) Light levels drop over time with conventional lighting systems, but power remains constant; (b) with a lumen maintenance system light levels stay constant, and energy is saved.

Lumen maintenance can be accomplished through the use of a dimming system with photosensor input. The control system for lumen maintenance is most cost-effective when large blocks of luminaires are controlled together. Group relamping to maintain all of the lamps at virtually the same lumen output is required for the system to be effective in reducing both energy and maintenance costs.

Task Tuning. Uniform illuminances are often provided throughout a space. With a task-tuning control strategy, however, the lighting system can be adjusted, or tuned, to provide local illumination as needed. Levels can be lowered in areas such as aisles and reception rooms and raised in areas where more difficult visual tasks occur. Considerable savings are possible through task tuning.² This strategy results in the efficient use of energy for lighting without sacrificing occupant visual performance.

Tuning is accomplished by varying the light output of individual or small groups of luminaires. Since it is necessary to tune the lighting only occasionally, upon a change in the space utilization or in the task being performed, the adjustment often can be done manually. Light controllers are capable of tuning a zone of luminaires.

Load Shedding and Demand Reduction. A building's lighting electrical bill can be effectively reduced by controlling lighting power demand for short periods of time. Selective reduction of illuminance in less critical areas can be particularly effective in regions where the peak electric power demand occurs in summer, because a reduction in lighting load also reduces the cooling load. Peak power demand charges are employed by many utilities to help avoid brownouts and blackouts, so the savings at peak periods can be substantial.

Aesthetic Control Strategies. Many spaces in commercial, institutional, and residential applications are used for more than one purpose. Different tasks require a variety of lighting conditions. Aesthetic controls provide the means to adjust the lighting to suit the purpose, to maintain human visual performance, and to change the mood of the space.

Aesthetic controls include switching and dimming. Dimming controls can provide dynamic effects or create strong focal points. Changes can occur rapidly to create excitement, or subtly to create a smooth transition between different room functions.

For many aesthetic applications it is necessary to control illuminance over a wide range. In a conference room, for example, a high illuminance would be required for reading tasks, whereas for a slide presentation the illuminance should be one-tenth or less of the reading level. The differences in needed illuminance are due to the differences in the task visibility and the adaptation of the eye to changes in illuminance. The square law curve for adaptation used by most controls manufacturers is shown in Figure 27-4. The curve shows, for example, that a measured illuminance of 25% of the original illuminance is perceived as a brightness of 50% of the original level. Audiovisual applications for controls generally require a measured illuminance of less than 10%, depending on the room reflectances, the screen employed, and the degree of note-taking required.

It is important to use a light source that can be appropriately dimmed. Incandescent and low-voltage incandescent sources can dim to zero output. Fluorescent sources can be dimmed to 1% output when used with certain dimming ballasts. Neon and cold cathode lamps can be dimmed to approximately 10% of maximum light output. HID sources can be dimmed to approximately 20% of maximum light

output, but they have a slow response time and strong color shifts, which make them poorly suited for aesthetic applications.

The strategies used for aesthetic control include manual controls, preset control systems, and central control systems. Manual controls (switches and dimmers) are commonly used in commercial, institutional, industrial, and residential buildings. If they are to be effective, manual controls should be simple and convenient to use. The number of control channels should be minimized to avoid confusing choices. Control panels should be clearly and permanently labeled (Figure 27-5). The appearance of the controls is also important. Switches and dimmers should match each other and fit into the overall architectural style of the space.

Preset control systems allow for several lighting channels to be controlled simultaneously. All channels are programmed to provide multiple moods or scenes. Each of these scenes can be recalled with the touch of one button (Figure 27-6). Preset systems are valuable in multifunction commercial spaces such as conference rooms and ballrooms. They are also used in residential applications for areas such as living rooms, dining rooms, and media rooms.

Central dimming systems are the most powerful of the group of dimming options. Like theatrical dimming systems, they have at least one central dimming panel with dimmers suitable for the type of load. The dimmers themselves are the power-handling devices. The control-function logic

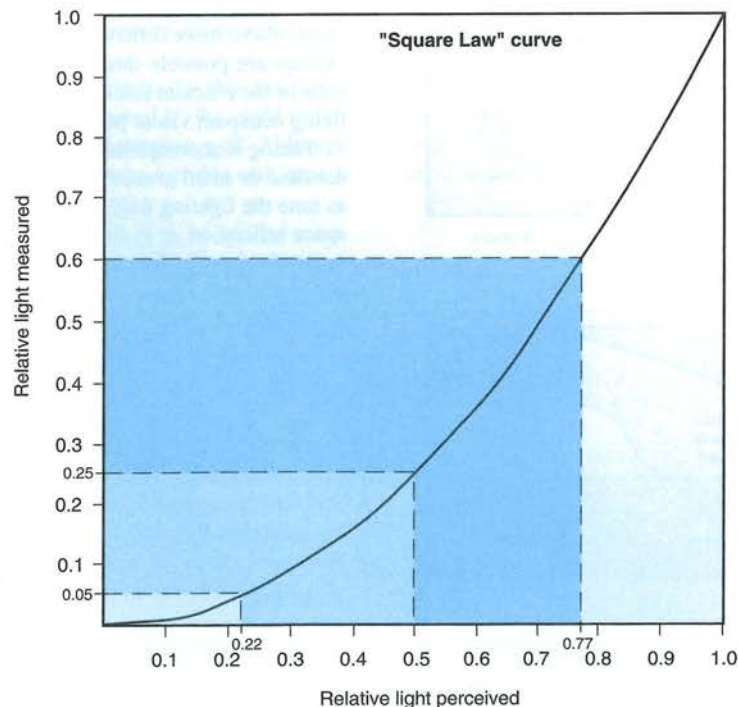


Figure 27-4. Square Law Curve—A presumed relationship between perceived illuminance and measured illuminance.

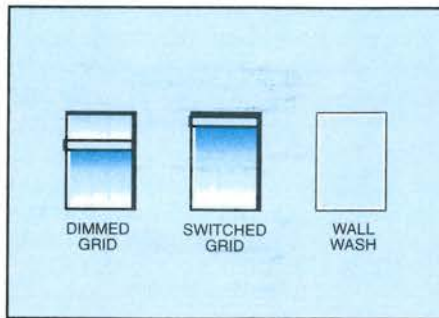


Figure 27-5. Switches and dimmers, clearly labeled for easy use.

is typically in the control stations, which can include processors and several forms of manual or preset controls.

Local, single-room systems typically consist of one control station with manual sliders or nondimming switches that can control large amounts of power. The dimmable wattage is limited only by the number of modules a dimmer panel can hold. These systems are easily expanded to multiple rooms and customized to offer many combinations of manual, preset, assigned, and time-clock control. They can incorporate energy reduction controls such as occupancy/motion sensors and photosensors and can handle emergency power functions. Some systems allow wireless remote control and can interface to audiovisual and other systems in both commercial and residential applications.

In divisible rooms, assignment control stations allow several independent lighting systems to be joined together through flexible master control. Hotel function rooms and convention center meeting rooms are the most common applications.

Whole-house systems are being used more frequently. Using local or small modular dimmers, a central computer, and master control stations, these systems can control every lighting feature. Many of these systems can also operate other electrical systems such as motorized curtains or whirlpool pumps, and they interface easily with burglar alarms, smart home systems, and other electrical control systems.

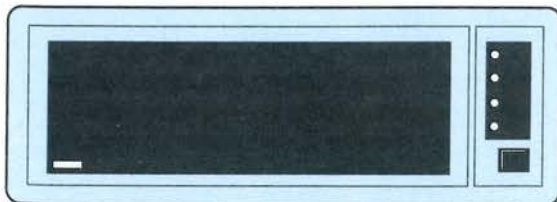


Figure 27-6. Example of multichannel preset station that provides four scenes of control for twelve channels of lighting.

LIGHTING CONTROL TECHNIQUES^{2,3}

Selection of the major control techniques is particularly important in the specification process. The following three categories establish the major choices: switching or dimming control, local or central control, and degree of control automation. After the strategies are decided, it is necessary to select the specific lighting control equipment to be employed.

Switching or Dimming

With switching control, lighting loads are switched on and off. This switching can be done manually with simple wall-box switches, remotely via relays or switchable circuit breakers, by a control system, or by occupancy sensors. It has been found that where the use of local switching controls can save energy, convenient switches might be used, but inconvenient switches are never used. Two-level switching in private offices is an inexpensive way to give the occupant the ability to modulate the environment in response to daylight or specific task needs. A different way to achieve switched light levels is through a light level switchable ballast. Rather than switching between lamps, the light level switchable ballast can reduce the light from all lamps in the luminaire.

Central switching systems can be less expensive to install per unit area than equivalent dimming systems and are most appropriate for strategies such as scheduling, where the switching action can be confined to unoccupied times. Switching techniques should be treated cautiously for other purposes, especially if the switching action can occur when the space is occupied, because sudden changes in the electric lighting can annoy building occupants, thus affecting productivity.³

In multiballasted lighting systems, switching can be used most effectively if the luminaires are split-wired. By split-wiring three- and four-lamp luminaires (Figures 27-7 and 27-8), multiple intensities can be provided in a single zone. With the help of a control system, full lighting can be provided for certain portions of the day while allowing a reduced lighting level (at reduced power) for times when less demanding tasks are performed. In retrofit applications, split-wiring can be expensive. Depending on the wiring system in place, relays can be installed near the circuit breaker panels to permit automatic control of blocks of lighting (Figure 27-9).

Occupancy or motion sensors can be used to control lighting in offices, conference rooms, and similar areas. In these situations, the addition of toggle switches or sensors with override switches to provide the manual off condition for certain applications (e.g., projections and maintenance) is recommended.

With dimming control, the illuminance in each zone can be varied smoothly and continuously to dynamically match visual requirements. Dimming control can be well suited to daylighting applications. However, the dynamic range of

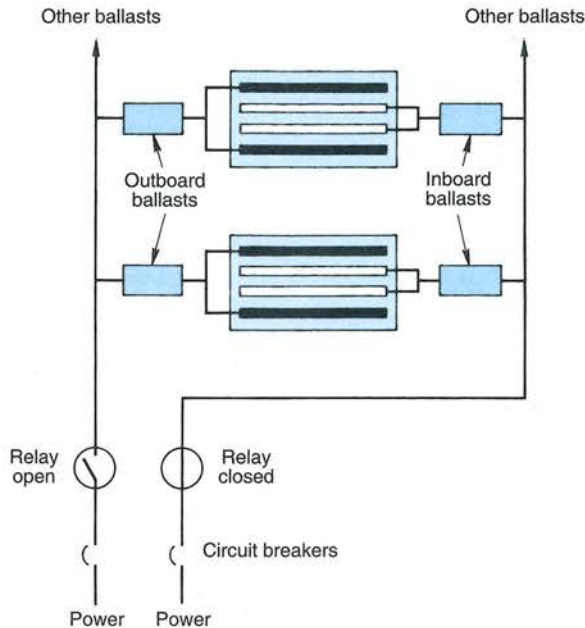


Figure 27-7. Split-level wiring scheme that permits three lighting levels (0, 50, and 100%) with four-lamp luminaires. Above luminaires are shown at 50% lighting levels.

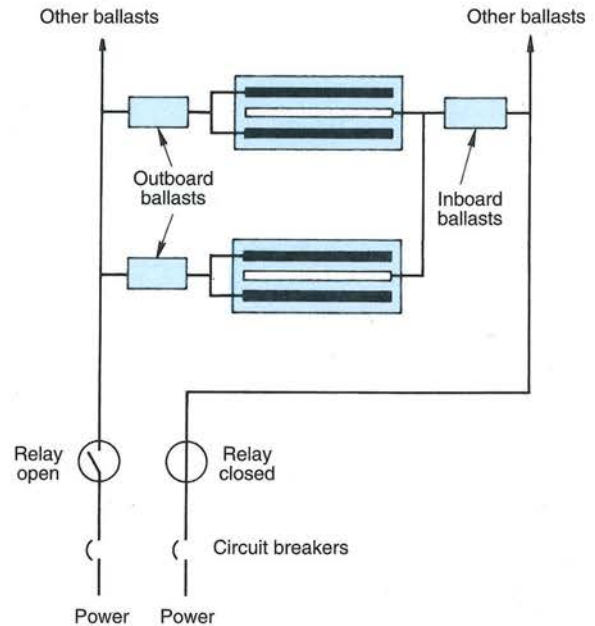


Figure 27-8. Split-level wiring scheme that permits four lighting levels (0, $33\frac{1}{3}$, $66\frac{2}{3}$, and 100%) with three-lamp luminaires. The above luminaires are shown at $33\frac{1}{3}$ % light levels.

daylight is much larger than it is for electric lighting (5:1), so caution must be applied in selecting the appropriate dimming control and sensitivity setting. Similarly, dimming is effective in saving energy by compensating for the gradual light losses that occur over time with all electric lighting systems (lumen maintenance strategy).

Local or Central

Lighting controls can be implemented in buildings using either a local approach, a central system, or some combination of the two. The two approaches are distinguished both by the size of the controlled areas and by how the control inputs are integrated into the system.

A local lighting system is divided into independently controllable zones, their size and shape typically dictated by the geometry of the building spaces (such as the locations of ceiling-high partitions, windows, or skylights) or according to functional need. Sensor inputs are wired directly to the local lighting and HVAC control rather than to a central location. Thus each module is essentially independent of other modules. The use of automatic occupancy sensors that can sense daylight availability can be especially effective in these situations.

Central systems generally combine many local zones. Some central microprocessor systems are intended to handle either the lighting and mechanical (HVAC) systems or both. Total building energy-management control and monitoring functions are easier with central systems.⁴

System Integration. One major advantage of a lighting control system is that the illuminance can be automatically adjusted to suit the activity or tasks at hand. With proper programming and sensors, some processors can control the lighting systems as well as the mechanical systems of the building. A common system permits the optimum control of energy use and also minimizes programming and training requirements. Through the use of a distributive processing

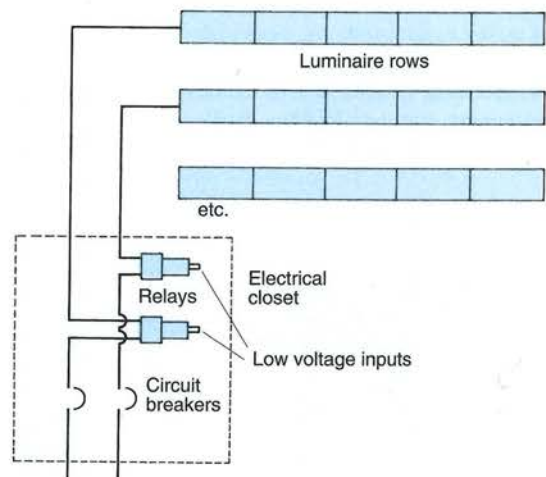


Figure 27-9. Installation of low voltage relays in an electric closet controlling different banks of luminaires.

configuration, the differences between mechanical and lighting inputs and control strategies are easily overcome. The local processor can be designed for the specific inputs and control outputs as well as the required interface with the central processor.

All lighting control systems contain three major components: a power controller, a logic circuit, and a sensing device. The communication and wiring system must link these components. The controller, such as a dimmer, relay, or switch, is the "business end" of a control system that electrically changes the output of the light source. The logic circuit is the intelligence that decides when to supply electric lighting, and how much. The logic circuit receives its information from a sensing device, such as a photosensor, an occupancy/motion sensor, or a timing device. Two or more of these elements can be combined in a single system (Figure 27-10).

Control strategies can have different but overlapping sets of hardware requirements. For some combination of strategies, such as daylighting and lumen maintenance, the hardware required for either is essentially identical to that required for both. Thus, the economic benefit of employing several strategies with the same hardware can increase the cost-effectiveness of the control system investment.

Hardwiring. There are many methods available for linking the lighting control system components. The control device itself (dimmer, relay, or switch) is usually hardwired to a lighting system before the supply and the ballast (line-side controls), as shown in Figure 27-11a. Some electronic ballasts incorporate circuitry to vary the output of the lamps over a wide range, effectively combining the control device and ballast into one integrated package (Figure 27-11b).

Power Line Carrier. The power line carrier is a communication method that is finding some application in retrofit control installations. By allowing communication between the processor and the control device directly over the existing power lines, extensive rewiring is avoided. However, some wiring systems in older buildings can significantly re-

duce the effective range of communications between the sensor, the processor, and the controller. There are limits to the overall capacity and speed of these systems. Care must be taken to ensure that all of the control devices on the power line are compatible as a system and suitable for the application. Many other factors contribute to a successful installation, but often poor power quality and pre-existing power line carrier systems (lighting, clocks, and/or other systems) can compromise the proper operation of these systems.

Radio Links. Radio-controlled systems eliminate the need for wiring between the sensor, the processor, and the controller. These systems are relatively expensive but have found application in outdoor systems and high-bay warehouses where the controlled luminaires are difficult to access. They are also suited to retrofit situations where control wiring would be difficult or expensive to install.

Radio frequencies from many sources can interfere with proper operation of this equipment. The required frequencies and bandwidths must be found for this system to work.

Degree of Control Automation and Zoning

Controls vary greatly in degree of automation, ranging from manual (wall switches) to highly automated. In terms of energy conservation, automatic controls can reduce energy consumption because they do not rely on human initiative. In terms of cost and occupant response, automatic controls are not always the most effective. Allowing occupants to override the automatic operation when required is very important, especially when programmable controls are used for scheduling purposes. A strict lighting schedule can be employed if automatic control can be locally overridden when necessary.²

Zoning. Compliance with energy codes, such as ASHRAE/IESNA 90.1, requires much closer coordination between the electrical engineer and the HVAC designer. Lighting and mechanical zones should match for coordinated control. In most cases this results in zones sized from 80 m² to 300 m²

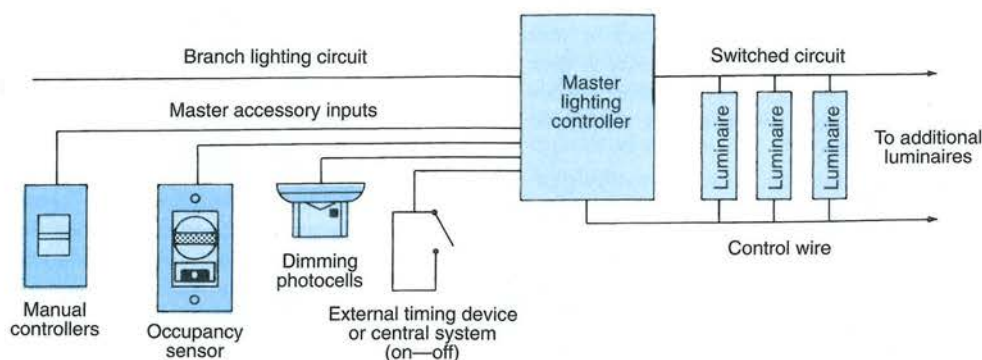


Figure 27-10. Diagram of a lighting control system.

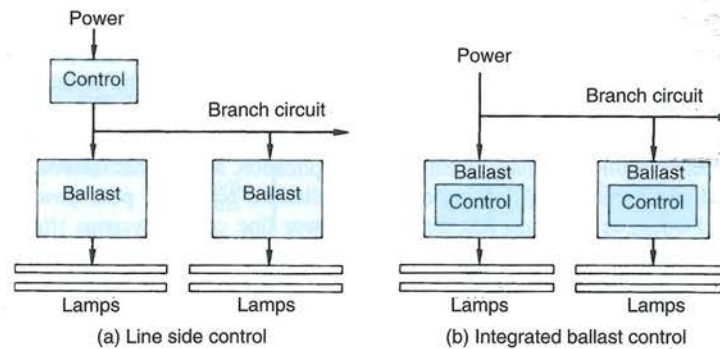


Figure 27-11. Lighting control operating lamps from (a) the line side of the luminaire; (b) integrated internally with the ballast circuitry.

(800 ft² to 3000 ft²). There is a tradeoff between the size of the control zone and the system cost. Smaller zones are more expensive (both in equipment and in installation costs) but offer greater flexibility and potential for reducing lighting operating costs. Some control strategies, particularly daylighting and task tuning, are best implemented with small control zones, 10 to 40 m² (100 to 400 ft²), while scheduling and lumen maintenance can be used effectively even if the control zones correspond to the area illuminated by an entire branch circuit, approximately 100 to 400 m² (1000 to 4000 ft²).

LIGHTING CONTROL EQUIPMENT

Manual Switching

The energy savings achievable through switching should be the initial consideration in developing the plan for lighting circuits. The most common practice is to allow manual control of lighting. The design and the location of the manual control affects the energy consumption of the building. Since the energy savings depend on the willingness of individuals to use the switching system, the convenience and flexibility of switching greatly affect the extent of any lighting energy savings. Occupants of private offices are the most likely to use switches to modulate the illuminance in their space and to do their part in saving energy. There is evidence that light switch reminder stickers can improve occupants' switching behavior.⁹

Each lighting plan presents a unique set of switching circumstances. The following general provisions should be considered:

1. Each separate office or area should have its own control switch, and those with daylighting should have at least two-level switching.
2. In large open spaces, similar work areas should be grouped together on one circuit.

3. When single- or two-lamp luminaires are used, adjacent luminaires should be placed on alternate circuits to provide for half and full light level.
4. When three-lamp fluorescent luminaires are used, the middle lamps should be connected to a separate circuit from the outside lamps. This produces three-level lighting systems with one-third, two-thirds, and full light level.
5. When four-lamp fluorescent luminaires are used, the inside pair of lamps should be connected to a circuit separate from the outside pair to provide half and full light level.
6. Task areas with high levels of lighting should be on separate switches.
7. Luminaires along window walls should be wired on separate circuits and be controlled independently.
8. Effective labels can cause occupants to use simple wall switches.¹⁰

Timing and Sensing Devices

Timing Devices. The function of the timer is to control lighting in response to known or scheduled sequences of events, that is, to turn off the lighting that is not needed. Timers range in complexity from simple integral timers (spring-wound) to microprocessors that can program a sequence of events for years at a time. Coupled with microprocessors, timers can control multiple events and lighting effects. As a general rule, some form of override must be provided to accommodate deviations from the preset schedule. The override should automatically reset to the programmed functions after a suitable period. Such timers can be effective in guest bathrooms in hotels, telephone equipment rooms, and certain stack applications, where occupancy sensors cannot effectively cover the entire area, and the area is not subject to complete blackout conditions if the lighting under timer control is extinguished.

With a simple integral timer, the load is switched on and

held energized for a preset period of time. Timer limits range from a few minutes to twelve hours. Some models have a hold position for continuous service. These units can handle lighting loads of up to 20 A.

An electromechanical time clock is driven by an electric motor, with contacts actuated by mechanical stops or arms affixed to the clock face. Time clocks have periods from 24 hours to 7 days and can include astronomical correction to compensate for seasonal changes. They can initiate numerous on-off operations. Some units are available with up to 16 hours of back-up power on the timing mechanism in case of power failure. Some can actuate a momentary contact switch to provide on and off pulses for actuating low-voltage relays or contactors. Wall-mounted (outlet box) units are also available to control local loads such as security lighting.

Electronic time clocks provide programmable selection of many switching operations and typically can be controlled to the nearest minute over a seven-day period. These devices offer the same switching options as the electromechanical time clock. Battery backup is available to protect the system from power outages.

Photosensors. Photosensors use electronic components that transform visible radiation (light) into an electrical signal, which is then used to control another system or lamp. Generally these sensors are either immune to or filtered from UV and IR radiation. Some sensors generate a control signal roughly proportional to the irradiance on the photosensor. The control signal can activate two modes of operation. In the first, the photosensor output activates a simple on-off switch or relay. In the second, a variable output signal is established and sent to a controller that continuously adjusts the output of the electric lighting.

When photosensors for interior applications are used in conjunction with relays for on-off control, they should utilize a "dead band," that is, the illuminance above which the lamps are switched off should be higher than the illuminance below which they are switched on. This prevents unnecessary on-off cycling near the threshold illuminance levels. It is also important to consider that switching lights on and off can disturb occupants. A photosensor can be an integral part of a luminaire, can be remote from the luminaire that it controls, or can control a circuit relay that operates several luminaires. A photosensor can also be used in conjunction with a time clock, which can switch lights off or reduce their output.

Photosensors used in outdoor applications are usually oriented to the north (in the northern hemisphere). This assures more constant illumination on the sensor as there is no direct sunlight contribution. The sensors are adjustable with respect to light levels for activation. Photosensors designed for outdoor lighting should not be used to control interior lighting because of their limited sensitivity and adjustability.

Systems that continuously vary their output proportionally in response to the varying photosensor irradiance are most effective when employed for window or daylight-

ing strategies. The photosensor detects an increase in illuminance and sends a compound signal to the controller to decrease the electric lighting illuminance. Systems that vary their output proportionally in response to the varying photosensor irradiance are most effective when employed for lumen maintenance. In response to the signal, the lighting system can be adjusted by stepped or continuous dimming.

The use of photosensors to control interior lighting is not trivial; proper design, placement, and calibration are critical.¹⁰ Several techniques are currently employed. Placement of the sensor on the task surface has the advantage of direct measurement of task illuminance, but there can be difficulty in wiring the sensor to the controller and in ensuring that the sensor does not damage and is not damaged by the task materials. The second and most common method places the sensor on the ceiling, oriented toward the task. A third method measures the daylight entering through the fenestration; best results are achieved when direct sunlight cannot fall on the sensor. A fourth method measures the external illuminance directly. All methods require the sensor output to be adjusted to match the illuminance on the task as closely as possible. An accurate and easy means to calibrate the response of the sensor is essential. Lumen maintenance strategies typically use the second method, and daylighting strategies can use any of the last three methods.

A further consideration with interior lighting is the amount of area controlled by one photosensor. The most important guideline is that all of the areas controlled by a single sensor should have the same general task activity, illuminance requirements, and surround. The space controlled should have the same daylight illumination conditions (amount and direction). The entire area should be contiguous, having no high walls or partitions to divide it. This is effective only if the task area monitored is truly typical and free of brightness extremes.

Occupancy/Motion Sensors.¹¹ The primary function of occupancy sensors is to automatically switch off luminaires (and, in some cases, HVAC equipment) when spaces are unoccupied, so as to reduce energy use. Electrical consumption is reduced by cutting the number of hours that luminaires remain on, and electrical demand is reduced by taking advantage of incomplete occupancy loads during periods of peak electrical use. Frequently, this method offers the best savings and payback of all control options. The failure of an occupancy sensor installation is almost always a result of poor sensor placement or incorrect equipment selection.

Occupancy/motion sensors provide local on-off control of luminaires in response to the presence or absence of occupants in a space. Occupancy is sensed by audio, ultrasonic, passive infrared, or optical means. These devices are designed to switch lights on as an occupant enters and keep them on while he or she remains in the space; lights are switched off after a preset time following the departure of the occupant. The normal movements of a person should

sustain lighting in the occupied space. Quiet activities such as word processing, reading, or using the telephone, however, may not be detected, and lights being switched off can frustrate occupants in these situations. These nuisance actions can be minimized by suitable product selection and proper sensor location. Occupancy/motion sensors can be mounted in several ways: they can be recessed or surface mounted on the ceiling, corners, or wall; they can replace wall switches; and they can plug into receptacles. The floor area covered by individual sensors can range from 15 m² (150 ft²) in individual offices or workstations to 200 m² (2000 ft²) in large classroom or assembly spaces. Larger areas can be controlled by adding more sensors. Occupancy/motion sensors can be used in combination with manual switching (on or off), timers, daylighting sensors, dimmers, and central lighting controls.

When selecting a sensor and planning for its location, the designer should ensure that all important movements within the controlled area are detected, subject to the avoidance of false positive responses; that is, responses to movement by inanimate objects inside the room or by people outside the entrance. It should also be recognized that the operating life of fluorescent lamps can be reduced by increased switching. The amount of the reduction can vary greatly and is dependent on the type of lamp, ballast starting circuitry, and the frequency of switching. The actual service life of the lamps, however, can be increased by the elimination of unnecessary burning hours. Research has determined that sensible lamp life, eliminating most premature lamp failure, balanced with meaningful energy savings, can be created with time delays of 15 to 30 minutes.¹²

It is common for occupants to override the action of occupancy sensors when they cause inconvenience or annoyance. A defeated occupancy sensor offers no energy savings, so proper operation from the very beginning is critical to the success of the installation.

Technically occupancy/motion sensors use an electrical or mechanical mechanism to trigger a switch device. Low total harmonic distortion (THD) electronic fluorescent bal-

lasts can create a high in-rush condition, which could cause premature failure of the occupancy sensor switching device. Some of the sensors on the market have a technical solution to managing this in-rush problem. Other technical considerations include the manner in which the sensor generates its own operating current; some devices use a neutral connection, and others use a trickle current through a connection to the ground. Finally, devices with solid-state switching devices can have a minimum load, whereas devices with dry contacts generally do not have a minimum load specification. Check the manufacturers' literature for additional details.

Large areas can require multiple sensors and multiple power devices for multiple circuits. Several combinations are available, with remote sensors, a variety of sensor technologies and coverage patterns, and voltage-specific power packs.

Ultrasonic occupancy/motion sensors transmit a low-power, high-frequency signal and receive a reflected signal, using the Doppler shift to sense movement in a space. The frequency of ultrasonic sensors is usually between 25,000 and 40,000 Hz (Figure 27-12). Ultrasonic occupancy/motion sensors are normally better at detecting small movements and detecting movements around modular walls such as would be found in restrooms and open offices. Also, most ultrasonic occupancy/motion sensors should not be mounted on ceilings above 4 to 5 m (14 to 16 ft).

There have been reports of ultrasonic occupancy/motion sensors interfering with hearing aids. Hearing aids operating above 40 kHz are not affected by ultrasonic occupancy and motion sensors. If the hearing aids are adjusted to operate within specifications, there should be no interference experienced.

Passive infrared (PIR) sensors detect the changes in infrared patterns across their segmented detection regions, tuned to the region of human body temperature (Figure 27-13).¹³ PIR occupancy and motion sensors have a line-of-sight coverage pattern with very predictable pickup patterns. They can be masked for controlling unwanted coverage

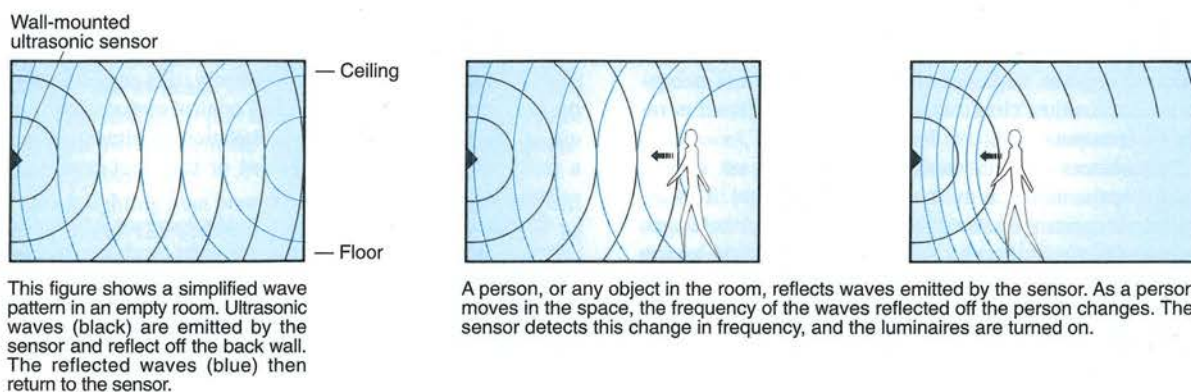
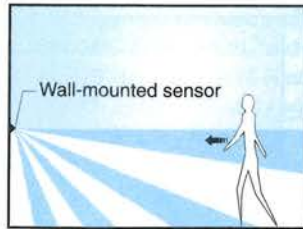


Figure 27-12. Example of motion detection with ultrasonic sensors.

Wall-mounted sensor:
Section view
Vertical fan patterns



Ceiling-mounted sensor:
Section view
Vertical fan patterns

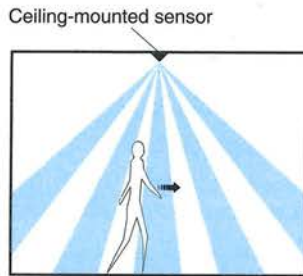


Figure 27-13. Example of motion detection with infrared sensors. The motion of a person through the pattern of receiver areas is detected as a change, and the luminaires are turned on.

areas. PIR sensors are especially suitable for areas that have high ceilings or high air velocities, as well as most general applications. They are most sensitive to movements perpendicular to the direction of view.

Dual-technology sensors are available that can use either UV or PIR signals or both. The logic and verification that can be incorporated in one unit can assist with applications where false triggering is especially problematic. Also, packaged sensors are available for desk-top applications to control task lights and computer monitors.

Central Processors

For centralized systems, the processor is the device that assimilates the data, determines the required change, and initiates action to effect the change. More sophisticated processors can respond to a number of complex lighting conditions in the space, collect power and energy-use data, and supply summary reports for building management and tenant billing. Processors range in complexity from a microchip in a controller to a large computer. Simplicity of operation and control, coupled with automatic operation in response to the actual environment, is essential.

In general, all processors operate in the same way. Input is received from a sensor such as a photosensor or clock, data are analyzed in accordance with a predetermined set of rules, and a system change is initiated. Systems can respond

to manual switches as well as to automatic functions (such as the time of day) and illuminance conditions. Outputs can include switching, dimming, and adjusting daylighting shading or reflection devices.

There are three types of processors: local, central, and distributed. In the local type, the processor is located in or adjacent to the device it controls. Sensor inputs go to a signal conditioner, either analog or digital, and are then fed to the processor. The central processor receives all inputs, analyzes the data, and then sends instructions to controllers located throughout a facility. This method allows coordinated control of all system elements. In distributed processing, the ongoing decision making is left to local processors, but a central processor orchestrates the entire system. It provides a time signal, operating parameters, and direction to specific points on an exception basis (one that overrides the normal routine). Most inputs are directed to the local processor. Analysis is performed locally, with only exception data being sent to the central processor. The advantage of this system is that it does not collapse from the loss of any one processor, and only the local processor has to be reprogrammed to accommodate changes.

DIMMING CONTROLS

Controllers for Incandescent Lamps

Equipment to control the light output of incandescent and tungsten-halogen lamps is readily available. Early lamp dimming controls were simply variable resistances connected in series with the lamps. The method wasted energy because some of the power saved in the lamp was dissipated in the resistor. An alternative to resistive dimmers was the autotransformer, which efficiently reduced voltage to the lamps, so transformer losses were relatively small. The autotransformer offers smooth, quiet, reliable dimming without introducing line interference, but it is bulky and heavy. Today, most dimming equipment relies on solid-state switching components that offer small size, design flexibility, and lower cost. This technology employs thyristors or transistors as the switching element to efficiently control the power to the lamps. However, the fast switching of these electronic devices can generate electromagnetic and audible noise as well as harmonic distortion that must be filtered.

Dimming incandescent and tungsten-halogen lamps affects the light output, life, and color temperature of the lamp. For example, a 12% power reduction decreases light output by 25%, and the lamp life triples. Figure 27-14 illustrates the effects of reduced voltage on light output, power, correlated color temperature, lamp life, and efficacy. Note that as the voltage is decreased, the light appears warmer. Tungsten-halogen lamps require certain minimum temperatures to operate correctly. To guarantee this, some control systems periodically operate the lamps at high levels for programmable times, to allow the halogen cycle to clean the

Figure 27-14. Change in Characteristics of Typical Incandescent Lamps Operated Below Rated Voltage

Input to Lamp (volts)	Light Output (percent)	Watts (percent)	Color Change (kelvin)	Life* (percent)	Relative Efficacy
120	100	100	0	100	1.00
110	75	88	- 100	300	0.85
100	55	76	- 200	1000	0.72
90	38	64	- 300	4000	0.59

* Based on filament temperature only. Other factors, shock and vibration, will also affect lamp life.

inside of the lamp envelope. There can be an impact on overall lamp life if the lamp is operated at too low temperatures for extended periods of time. For this reason it is better to select lamps close to the desired lumen output rather than dimming high wattage lamps to lower levels.

The dimming of low-voltage incandescent and tungsten-halogen lamps is very similar to the dimming of line-voltage incandescent lamps, with a few important exceptions. Special dimmers should be used that are specifically designed to dim these specialized loads and to protect the lighting system from the problems associated with the low-voltage transformers. Magnetic transformers require supervisory circuitry to prevent dc current from reaching the load. All dimming of low-voltage loads requires the use of approved dimmable transformers. This ensures that the transformers do not fail during the dimming process, and that they do not make objectionable noise while in operation.

Controllers for Fluorescent Lamps¹⁴

The fluorescent lamp is the primary light source for commercial and retail applications. Unlike the incandescent lamp, which is a pure resistive load, the fluorescent lamp is a complex negative-resistance load requiring a ballast to maintain the proper electrical input for both starting and operation. Simply reducing the input voltage, as is done to dim incandescent lamps, extinguishes the arc at some point, as well as reduces the life of the lamp. Equipment is available to dim these lamps when operated with standard magnetic ballasts, magnetic dimming ballasts, or electronic dimming ballasts. Many new products are available to control fluorescent lamps on highly efficient electronic ballasts (Figure 27-15).

Fluorescent lamps operated with special electronic dimming ballasts, typically those that dim down to 10 to 20% of maximum light output and with enhanced low level capability (and higher cost), can be dimmed to less than 1% of full light output without producing flicker. Some electronic ballasts are also designed to reduce the electrode filament voltage at full light output and to restore it when the lamps are operated in the dimmed mode at low arc current. This extends the lamp life and reduces the power requirement at full

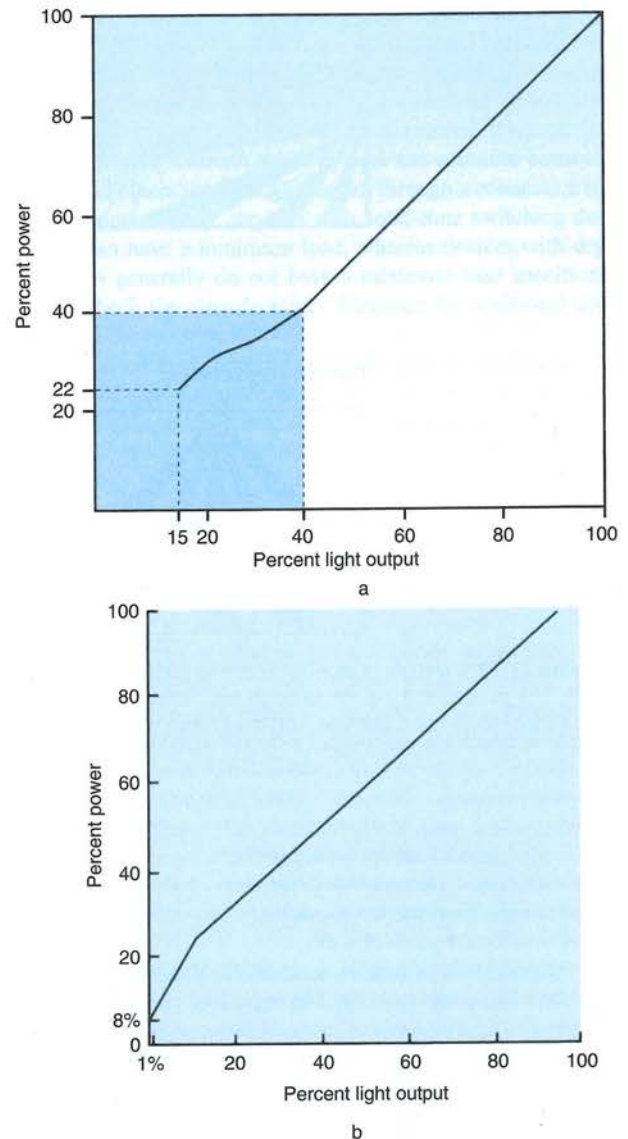


Figure 27-15. Relative light output as a function of power for (a) a two-lamp, 34-W, rapid-start fluorescent system with standard core-coil ballast. Minimum level of lighting adjustment is shown as 15% light output at 22% power; (b) three-lamp, 32-W, T-8 rapid-start fluorescent system with electronic ballast. Minimum level of lighting adjustment is shown as 1% light output at 8% power.

light output (Figure 27-15b). Proper luminaire grounding is essential for stable lamp operation, especially at low light levels.

Control Methods. There are several types of electronic dimming ballasts on the market today. These ballasts differ

in the way they are controlled by one of three methods: phase control, PWM (pulse width modulation), and low-voltage control (typically 0 to 10 V dc). The PWM control is the least used scheme, as it utilizes a high-frequency square-wave signal over separate control wires to dim lamps down to approximately 10% of maximum output. The main advantage of PWM control is its ability to control a large number of ballasts per controller.

The phase control method gives the user the most flexibility since it dims lamps to 1%. It uses a controller that controls up to 60 ballasts. This system gives very uniform dimming and lamp stability. Its main drawback is the high initial cost for equipment and installation.

The third control type is low-voltage control. A dc voltage is sent to each ballast via separate control leads. A single control device (e.g., slide dimmer, photosensor, building management system [BMS], etc.) can control 60 to 80 ballasts, with a stable dimming range of 100% to 20% or lower, depending on the low level capability of the ballast. This type of control is typical of many energy management applications.

Controlling the light output via low-voltage signals allows electronic dimming ballast systems to be more flexible than magnetic ballast systems based on conditioning the ballast input power. Large banks of electronic ballasts can be controlled as readily as a few. Thus, lighting control strategies such as task tuning, daylighting, and load shedding generally require modular control. Scheduling and lumen maintenance can be readily accomplished with electronic dimming ballast systems, since the ballast is controlled independently of the distribution system.

Multilevel Ballasts. Both magnetic and electronic multilevel ballasts are available. These provide the ability to be switched between two or more illuminances. They provide a low-cost, but limited control approach for dimming and can be used in some cases to satisfy energy codes.

Controllers for HID Lamps

High-intensity discharge (HID) lamps can be controlled using control equipment similar to that used for dimming fluorescent lamps. The long warmup, restrike delay, and color shift associated with HID lamps, however, can limit their applications. On-off control of HID lamps is most commonly used where there are long on and off periods, as for outdoor and roadway applications, where switching generally occurs twice a day. These typically use a photocell.

Multilevel ballasts are available for HID lamps, allowing the illuminance to be changed in steps. This technique is practical in warehouses, parking garages, tunnels, and daylighting applications. Recently, retrofit kits have become available to allow some existing facilities to have multilevel switching added to previously installed HID lamps. Equipment is available to dim HID lamps continuously to less

than 20% of full light output. Color shift limits the range that can be used in some applications. Metal halide lamps shift color toward blue-green, and high-pressure sodium lamps shift color to yellow. The change in color becomes noticeable below 60% of rated lamp power for metal halide and 40% for high-pressure sodium lamps. See Chapter 6, Light Sources, for information on the relative change in power and light output for HID.

COST ANALYSIS

The approach used to evaluate the economics of lighting systems can be extended to include systems with controls.¹⁵ Fundamentally, the procedure involves adding the cost of the control system to the rest of the lighting system equipment costs and determining how the use of the controls affects operating costs. Since lighting controls can affect not only the operation of the lighting system but also other building energy systems, all of the system interrelationships must be considered. In office buildings, for example, lighting controls that vary the output of the general lighting, perhaps in response to daylight, also change the amount and location of heat generated in the building. As the building's heating and cooling systems take this into account, the HVAC costs are affected. Some lighting control systems can also affect the electrical system; for example, by changing the power factor, high in-rush currents, and high harmonic currents, the performance of the lighting system itself can be altered in terms of efficacy, lamp life, and ballast life.

Energy savings depend on the size of the space, the availability of daylight, the work schedule, the kinds of activities performed, and the attitude and training of the occupants. For example, if the users are motivated to switch lights off each time they exit the area, then the installation of occupancy/motion sensors does not result in significant energy savings.

To estimate the energy that could be saved by using automatic controls, the areas to be controlled should be divided into smaller areas of similar function and occupancy, such as private offices with windows and open-plan sales offices. Users should establish a plausible use scenario for each small area, including:

- Hours of use
- Fixed or flexible work schedules
- Weekly, monthly, or yearly changes in the schedule
- Periods when areas are unoccupied, such as breaks, lunch, end of day, before cleaning
- Cleaning crew schedules
- Use of daylight to reduce electric lighting during daylight hours

The sum of the projected savings from small areas provides the total potential savings.

Cost Considerations

Some costs normally associated with the installation and operation of lighting control systems include:

- Control hardware, including sensors, control and monitoring station equipment, cabling and overcurrent protection
- Interface equipment, such as multiplexers in cases where control signals are carried by the power wiring, or data links and interconnection devices between controls and the telephone or onsite computer system
- Installation and setup labor, since several different skills (and therefore costs) can be involved in handling both signal and power level wiring, calibration, and checkout
- Maintenance labor and spare parts
- Energy costs and utility rate structures

Economic Analysis Techniques. Lighting controls are frequently cost justified on the basis of expected energy cost savings over a period of time. Methods of comparing the cost with the savings are explained in Chapter 25, *Lighting Economics*.^{15,16}

Sources of Cost and Performance Data. Although cost information for lighting control hardware is easily obtained, performance information that affects operating and other system costs is not readily available and can be very site specific. The main operating-cost factors are the system input power and operating hours. Fairly accurate estimates for on-off control systems can be made if the operating period of the system is known, but systems with variable power inputs must be measured or carefully simulated. It can be helpful to construct a profile of system input power versus time or use computer modeling, especially if daylighting, time-of-day utility rates, or other special considerations apply.

Studies reveal that the impact of occupancy detectors is highly application dependent. The energy reduction realized from the proper use of occupancy sensors has been measured to be from 10 to 50%.¹³

IMPACT OF LIGHTING CONTROLS

Effects on the Whole Building

HVAC Effects. Lighting can be responsible for a major portion of a building's HVAC load. Thus, lighting electrical loads have a major influence on both the air-conditioning loads and fan operation. Lighting electrical loads affect the initial cost of the HVAC system as well as its annual energy consumption. If lighting controls are utilized to reduce the lighting energy consumption, it is important that the HVAC system and controls be designed to respond to changes in the operation of the lighting system. Furthermore, with the trend toward the use of daylighting to augment the electric

lighting system, it is also necessary to consider the effects of the glazing system on the heating and air-conditioning system and its controls. Daylighting can increase the initial cost and the annual energy consumption if the daylighting system is not carefully designed. Indeed, payback can be longer with daylighting controls. For example, a daylighting system can increase the necessary summertime cooling load of a building by letting more heat into the building. Many modern occupancy sensors have dedicated control outputs for the simultaneous control of lighting and HVAC equipment.

By properly integrating the HVAC system and its controls with the lighting system and its controls, often both the initial cost of the HVAC system and energy consumption can be reduced. In order to achieve these benefits, the HVAC system must be properly designed with zoning and effective controls. The type of HVAC system is extremely important if full savings are to be achieved from lighting controls, especially in existing buildings where the air-distribution system is either a multizone, double-duct, or terminal reheat system; these systems supply a constant amount of air and vary the supply air temperature in order to maintain the space temperature.

In recent building designs, the use of multizone and terminal reheat systems has been eliminated by building energy codes. Most commercial systems use numerous small single-zone units or variable-air-volume (VAV) systems where the space temperature is maintained by an air supply of a constant temperature and varying volume.

Lighting controls can be integrated with the HVAC system within the building energy management and control system (EMCS). The primary application is the time scheduling of the start and stop of the various loads. The EMCS computer can also be used to consider the time of imposition of the various loads required for optimal start and stop and the thermal storage effects of the building mass.

Another consideration that affects the energy consumption of the HVAC system is the part-load efficiency of the heating and air conditioning, including the energy dissipated by fans and motors. Unless the HVAC system components and controls are designed to take into account the part-load efficiency, most of the potential HVAC energy savings from the lighting controls will not be realized.

Electrical Equipment Effects

Switching. Controls that switch lamps on and off excessively can reduce fluorescent¹² and HID lamp life. Increased cycling does not decrease ballast life or reliability. The actual service life of lamps can be extended by the elimination of unnecessary burning hours.

Interference. Radio frequency interference (RFI) or electromagnetic interference (EMI) is inherent in all control systems that rapidly switch a portion of input power. There are specific standards and limits to the radio noise permitted in the United States. The Federal Communications Commis-

sion (FCC) publishes these standards (FCC, Part 15 or 18)¹⁷ and regulates the manufacture of devices that can emit radio noise. The Food and Drug Administration (FDA) publishes separate standards for radio noise for devices used in hospital environments. The FCC is concerned with all types of radiating devices, including various types of occupancy/motion sensors.

There are two areas of concern with regard to radio noise: conducted emission and radiated emission. Conducted emission is the noise fed directly into the power line by the device drawing power from that line. Radiated emission is the electrical noise radiated by the lamps in the luminaire, with the power line possibly acting as an antenna. Conducted emission follows the power line itself as a path of propagation. Generally, at high frequencies this noise is limited to the downstream portion of the circuit, from the branch transformer to the devices in question.

In most commercial and industrial buildings the lighting power circuits are contained within metal conduits. These conduits attenuate radiated electromagnetic energy and limit the radio noise to the circuits contained within the same conduit. Conducted emissions are of concern to the extent that they interfere with the lighting control system and any other devices on the same branch circuit feeds, such as computers or security systems. Control systems use passive and active filters to keep the conducted emissions within the allowable limits.

With shielded power lines, radiated noise is limited to the radio noise emitted directly from the controller and luminaire. It is of concern to the extent that other devices within the immediate area of the controller and luminaire can be affected. The primary antenna within the luminaire is the lamp itself. While all ballasts, lamps, and control systems emit radio noise that can interfere with some equipment, there are precautions that ballast and control manufacturers can take to reduce such noise. For conventional ballasts, noise filters are available. For solid-state high-frequency ballasts, which emit more radio noise than conventional ones, the noise is of a type and magnitude that can be more easily suppressed or designed out of the ballast. There are also luminaires with conductive lenses specifically designed to attenuate the EMI radiated by the lamps.

Power Quality

The power quality of electrical switching systems has become a concern to utilities with regard to power factor, safety, and interference. Most incandescent dimming techniques use phase control, in which the voltage to the lamp is reduced by high-speed switching. This distorts the sinusoidal line current, producing other frequencies and leading to a decrease in the power factor.

The designer should be aware of potential harmonics, as they can overload the neutral conductor in three-phase electrical distribution systems, which can damage its insulation, overheat transformers, and distort the voltage at points of

coupling. In addition, if only a single leg of a three-phase system is dimmed, the system becomes unbalanced, further increasing the neutral current. In practice no problems have actually been attributed to the generation of harmonics by lighting control systems to date, but designers and engineers should become familiar with the issues when using these advanced lighting technologies.

Very low harmonic content electronic ballasts can have a high-in-rush current, associated with the front end power filtering. Consult the specific manufacturers' literature for detailed information on this.

Human Performance Effects

Lighting control systems can have a positive effect on the working environment, provided that they add to the comfort and the aesthetics of a space. Controls can have further economic benefit if the productivity of the occupants is increased. This can be true, for example, in spaces where visual display terminals (VDTs) are used because the brightness of reflected images is reduced by dimming the lighting. In general, the ceiling and task lighting can be controlled in zones over a wide range of illuminance to adjust the lighting to the specific needs of the spaces.¹⁸

Care should be taken when attempting to reduce peak power demand or energy use to ensure that illuminance is not reduced below that required for visual tasks in the space. Audible noise, flicker, and source color changes caused by dimmer controls can also affect performance.

Illuminance. The illuminance determines the visual adaptation level, which has been demonstrated to affect performance in visual tasks such as reading, inspecting, and assembling (see Chapter 3, Vision and Perception). Control systems must be designed so that the lighting system can provide proper illuminance for these tasks.

Audible Noise. Lighting control systems can produce audible noise in the environment, which can be a source of annoyance. The manufacturer should be consulted to minimize the noise produced by the control system. Noise control strategies include careful lamp selection, enhanced dimmer filtering, and remote dimmer locations.

Flicker. Controls that modify waveforms can cause excessive flicker. Flicker is noticeable if the variation in light amplitude is sufficiently high (see Chapter 3, Vision and Perception, and Chapter 6, Light Sources). Even imperceptible flicker can cause eyestrain and fatigue at 50 Hz.¹⁹ While theoretically less of a problem at 60 Hz, some people are still sensitive to flicker. Proposed control systems should therefore be examined for their effect on flicker.

Flicker is typically greater with uncoated HID lamps than with fluorescent lamps. This is because the phosphors in a fluorescent lamp continue to generate light throughout the ac cycle. Most phosphor-coated HID lamps exhibit this reduced flicker. HPS lamps have high flicker because of the

rapid recombination of sodium ions. Lamps should be selected that minimize flicker. Electronic fluorescent and HID ballasts should be selected because they drive the lamps without flicker. Further flicker reduction can be achieved with HID lamps by placing luminaires in a room on different supply phases.

Color Changes. During lamp dimming, there can be a small shift in lamp color with fluorescent lamps. This color shift is not usually considered significant, but it is noticeable, especially with warm CCT lamps. Other light sources, including incandescent lamps, exhibit a more significant color shift. Care must be exercised when employing such lamps. They should not be dimmed to levels that alter the aesthetics of the space, cause discomfort to the occupants, or affect tasks in which color rendition or discrimination are essential. One acceptable approach is to limit the range of dimming so that no color shift is apparent. On the other hand, the shift in incandescent lighting to a lower color temperature by dimming can actually be desirable in certain applications, such as restaurants, where a warmer atmosphere can be inviting.

REFERENCES

1. IESNA. 1991. *Lighting economics: An intermediate approach to economics as applied to the lighting practice*, IES ED-150.9. New York: Illuminating Engineering Society of North America.
2. Rubinstein, F., M. Karayel, and R. Verderber. 1984. Field study on occupancy scheduling as a lighting management strategy. *Light. Des. Appl.* 14(5):34-38, 40-45.
3. Rea, M. S., ed. 1984. *Lighting Control: Proceedings of the CEA/DBR Symposium*, Ottawa, June 28, 1984. Ottawa: National Research Council Canada.
4. IES. Energy Management Committee. 1987. *IES design considerations for effective building lighting energy utilization*, IES LEM-3-1987. New York: Illuminating Engineering Society of North America.
5. Lawrence Berkeley Laboratory. 1985. Controlite 1.0: *Lighting control systems and daylighting analysis program*, LBL-17444. Berkeley, CA: Lawrence Berkeley Laboratory.
6. IES. Daylighting Committee. 1979. *Recommended practice of daylighting*. IES RP-5. New York: Illuminating Engineering Society.
7. National Bureau of Standards. 1977. *Window design strategies to conserve energy*. Prepared by S. R. Hastings and R. W. Crenshaw. Building Science Series 104. Washington: U. S. Government Printing Office.
8. Bryan, H., W. Kroner, and R. Leslie. 1981. *Daylighting: A resource book*. Troy, NY: Rensselaer Polytechnic Institute.
9. Rea, M. S., R. F. Dillon, and A. W. Levy. 1987. The effectiveness of light switch reminders in reducing light usage. *Light. Res. Tech.* 19(3):81-85.
10. Rubinstein, F. 1984. Photoelectric control of equillumination lighting systems. *Energy Build.* 6(2):141-150.
11. New York State Energy Research and Development Authority. 1982. *Occupancy controlled lighting: Energy savings demonstration and analysis*, ERDA 82-83. Prepared by O. Turner. Albany, NY: New York State Energy Research and Development Authority.
12. Carriere, L. A., and M. S. Rea. 1988. Economics of switching fluorescent lamps. *IEEE Trans. Ind. App.* 24(3): 370-379.
13. Maniccia, D. 1997. *Specifier reports: Occupancy sensors*. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.
14. Alling, W. R. 1983. The integration of microcomputers and controllable output ballasts: A new dimension in lighting control. In *Conference record: Industry Applications Society, IEEE, IAS-1983 annual meeting*, [Mexico]. New York: Institute of Electrical and Electronics Engineers.
15. McGowan, T. K. 1983. The economic analysis of lighting systems with controls. Proceedings: 20th session. Commission Internationale de l'Éclairage, Amsterdam, August 31-September 8, 1983. Paris: Bureau Central de la CIE.
16. Verderber, R. R., and O. Morse. 1981. Cost-effectiveness: Long-life incandescent, circular fluorescents and energy buttons. *Elec. Constr. Maint.* 80(11):55-58, 81.
17. Federal Communications Commission. [Latest issue]. *Industrial, scientific, and medical equipment*, 47 CFR 1.A.18; *Radio frequency devices* 47 CFR 1.A.15. Washington: U. S. Government Printing Office.
18. Maniccia, D., B. Rutledge, M. Rea, and N. Narendran. 1998. *A field study of lighting controls*, Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.
19. Wilkins, A. J., I. Nimmo-Smith, A. I. Slater, and L. Bedocs. 1989. Fluorescent lighting, headaches and eyestrain. *Light. Res. Tech.* 21(1):11-18.

Lighting systems must be maintained to assure the lighting quantity and quality intended, whether for task performance, safety, or aesthetic reasons.¹ System components have a finite life and at some point in time must be replaced. Lamp performance changes over time before failure. Dirt accumulates on luminaire and room surfaces.

Lack of maintenance can have a negative effect on human performance, perception of an area, safety, and security. It can also waste energy. The combined effect of equipment age and dirt depreciation can reduce illuminance by 25 to 50% or more, depending on the application and equipment used. At the same time, the owner of the lighting system continues to pay the same amount for electricity as if the lamps were new and the lamps, luminaires, and room surfaces were clean.²

All of these factors tend to reduce illuminance or change the lighting quality. To take the above causes of light loss into account, lighting systems are generally designed with a light loss factor to provide from the onset a higher illuminance than that recommended for the task in the space.³

The most effective method of consistently maintaining illuminance and lighting quantity at the lowest operating and maintenance cost is through a planned program. Planned lighting maintenance entails group relamping, cleaning lamps and luminaires, and replacing defective or broken components on a scheduled basis. Painting and maintaining room surfaces are also important.⁴

CAUSES OF LIGHT LOSS

Lighting maintenance means action to recover light losses due to the following:⁵

- Lamp lumen depreciation
- Dirt accumulation on lamps and luminaires
- Lamp failure
- Luminaire surface deterioration
- Room surface dirt accumulation

Lamp Lumen Depreciation

As a lamp is operated, its lumen output gradually decreases until failure occurs. This is called lamp lumen depreciation and is characteristic of all lamps, although the rate of decrease and the overall lamp life differ for each lamp type (see Chapter 6, Light Sources).

Dirt Accumulation on Lamps and Luminaires⁶

As dirt accumulates on a lamp, it reduces the amount of light being emitted. As dirt accumulates on luminaire surfaces, it acts to reduce the amount of light reflected or transmitted by those surfaces. Dirt buildup on the luminaire's surfaces can also affect light distribution; for example, dirt on a specular aluminum reflector in a high-bay luminaire can widen the lighting distribution of that luminaire. Such a change results in lower illuminance on the workplane. The total amount of light loss due to dirt depreciation depends on the type and amount of dirt accumulated, the lamp's type and shape, and the luminaire's design and finish.

Two types of luminaires built to resist dirt accumulation are ventilated luminaires and filtered or dust-tight luminaires. Ventilated luminaires tend to collect less dirt than those with closed tops. The temperature difference between the lamp and the surrounding air causes convection currents that help carry dirt through the luminaire openings rather than allowing it to accumulate on the reflector. Filtered or dust-tight luminaires or reflector lamps minimize dirt accumulation because the lamp and reflecting surfaces are protected from dusty air.

Light losses due to dirt depend on the rate of accumulation and the characteristics of the dirt. For example, dirt buildup occurs much faster in a foundry than in a well-ventilated office. The dirt found in a suburban office is different in amount and type from dirt in an office located in an industrial area. Black steel-mill dirt is very different from the light-colored dust found in a woodworking shop. Thus, dirt accumulation affects luminaire performance differently in each of these situations.

Lamp Failure

A lamp failure decreases the local illuminance and thus affects lighting uniformity. It can also pose a hazard to other luminaire components. For example, in some fluorescent circuits, when one lamp fails, others on the same ballast glow dimly and may also fail. This can also cause rectification and high ballast current, causing the ballast either to fail immediately or to experience reduced life.

Luminaire Surface Deterioration

Luminaire construction materials differ in their ability to reflect light and resist deterioration. Porcelain enamel, for exam-

ple, retains its high reflectance and is relatively easy to clean. Processed aluminum finishes tend to depreciate at a lower rate than painted finishes. Plastics (acrylics, cellulose, polycarbonates, and vinyls), as light-controlling materials, change over time. Exposure to ultraviolet (UV) and infrared radiation (IR) causes the color and transmittance of plastics to change. The rate of change depends on the lamp type, its distance from the plastic, and the temperature to which the plastic is subjected during operation periods. Additionally, improper cleaning materials and techniques can cause added changes in transmittance because of chemical action or surface scratching.

Room Surface Dirt Accumulation

Light reaching the work plane comes directly from the luminaires in the room and from the reflected light from room surfaces. Thus, dirt accumulation on room surfaces reduces the amount of light on the workplane. Cleaning and regular repainting of walls and other surfaces will reduce the effect of dirt accumulation on these surfaces.

The effects of these light loss factors are shown in Figure 28-1. These and others are discussed in Chapter 9, Lighting Calculations.

PLANNED MAINTENANCE TECHNIQUES

During the design of a new or retrofit lighting system, an effective and properly executed maintenance plan can minimize the required number of luminaires needed for a space, thus minimizing first costs and energy costs.^{4,7} The primary maintenance techniques are group relamping and cleaning. During and between relamping and cleaning, the system can be inspected for defective or broken components and other problems.

Group Relamping

Group relamping entails replacing all of the lamps in a system together after a fixed interval, called the economic group relamping interval. Group relamping can reduce the cost of operating a lighting system while keeping illuminance levels close to the design value. As discussed above, if a lighting system is analyzed during the design phase and group relamping is judged economical, then lower illuminance can be specified at system commissioning.

Group relamping saves labor costs. It typically costs less per lamp to replace all of the lamps in a system at one time than it does to replace them one by one as they fail. If the labor savings are worth more than the value of the used lamps, then from an economic standpoint it makes sense to discard used and depreciated lamps, even though they may still have some burning hours remaining. A useful rule of thumb is that group relamping should be examined if the labor cost of spot-replacing one lamp, less the cost of group-relamping one lamp, exceeds the cost of one new lamp. Large-quantity lamp purchases also lower unit costs.

Analysis techniques are available to determine the economic group relamping interval. These are based on the mortality rates of the lamp (the probability of failure as a function of time), the labor rates involved, the cost of the lamp, and its depreciation rate. Typically, the most economical time to group relamp is between 70 and 80% of rated life. This is just before the majority of lamps are expected to fail, when the greatest labor costs can be saved, and when lamp lumen depreciation makes the lamps uneconomical to continue operating from a cost-per-lumen standpoint. The calculations should take into account the cost of replacing spot failures between group relampings so that lighting quality and appearance are also maintained. Group relamping also includes a scheduled period when relamping can be economically combined with installation of new luminaire components such as specular reflectors, energy-efficient lamps, energy-efficient ballasts, and other components that improve the performance of the system.

- A three-year study known as the Luminaire Dirt Depreciation Study is nearing completion. This study has been jointly sponsored by the International Association of Lighting Management Companies (NALMCO) and IESNA and has been funded by the U.S. Environmental Protection Agency. The project involves taking a time series of field measurements in individual luminaires in nonindustrial interior environments.
- The results of this project will be used to update the Luminaire Dirt Depreciation factor characteristics that are part of the lighting system design process. The new reliable dirt depreciation data also will be used in life cycle cost analysis.
- It has been assumed that present interior environments are cleaner than those of the 1950s, when the existing maintenance data were developed. To the extent that this can be quantified, the initial excess illuminance allowance for dirt depreciation can be reduced. Such a reduction reduces the initial lighting system cost, the lighting system power requirements, and the heat load placed on other building components.

Periodic Planned Cleaning

Cleaning the lighting system usually entails washing or otherwise removing dirt from the luminaires (see Figure 28-2), occasionally cleaning and repainting room surfaces, and occasionally cleaning air supply vents to prevent unnecessary dirt distribution. Cleaning is another service that can economically be combined with group relamping; in environments with high concentrations of dirt or dust in the air, it should be performed often. As in the case of group relamping, periodically cleaning luminaires delivers more light per lighting dollar and ensures more consistent illuminance through the life of the lamps.

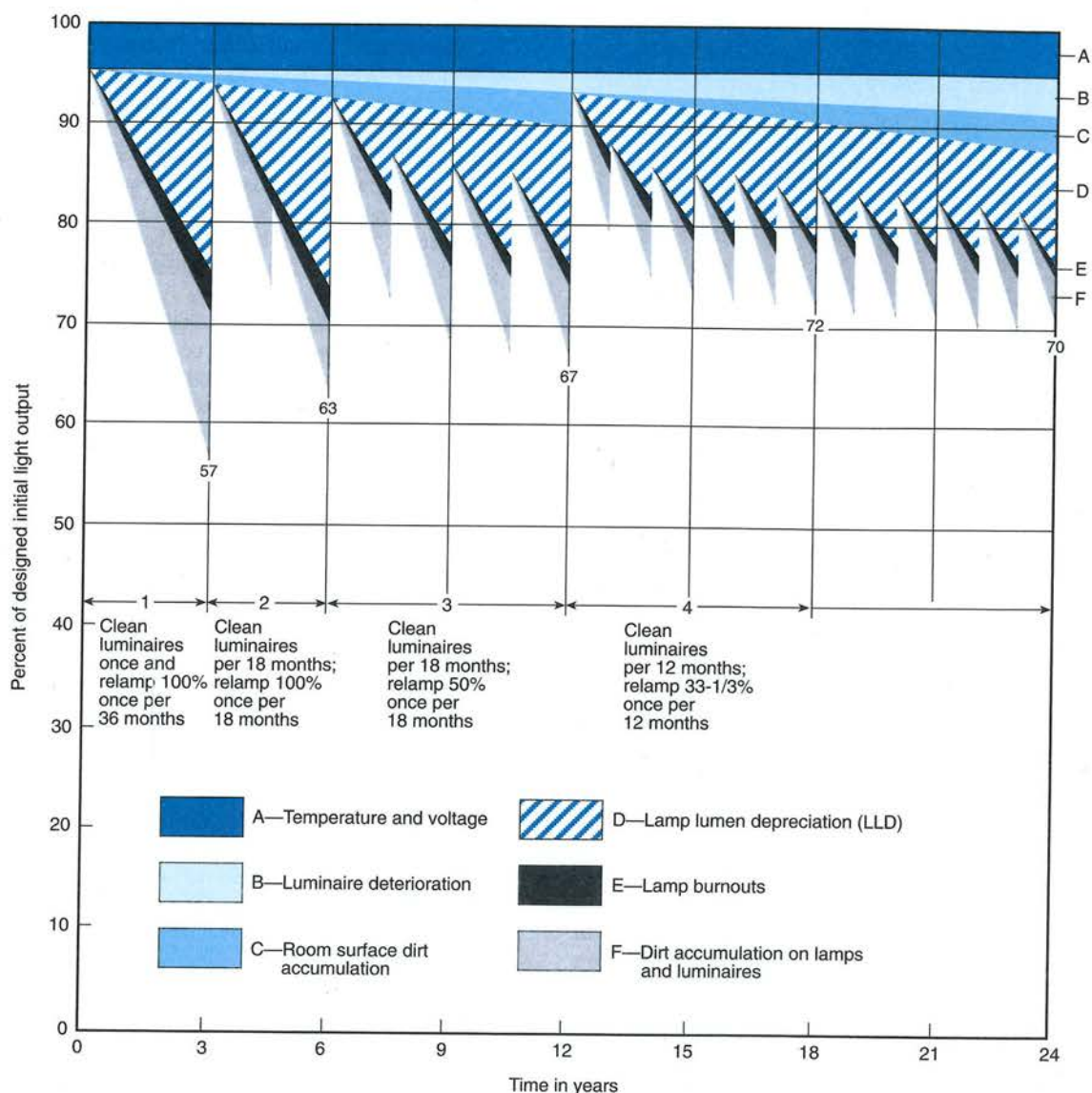


Figure 28-1. Effect of light loss factors on illuminance level. Example above used 32-W T-8 cool-white rapid-start lamps in recessed troffers, operated 10 hours per day, 5 days per week, 2600 hours per year. All four maintenance systems are shown on the same graph for convenience. For a relative comparison of the four systems, each should begin at the same time and cover the same period of time.

OPERATIONS: PROGRAMS AND METHODS

Planning

Lighting systems are becoming more complex. As a result, the requirements for resources, expertise, and competence are increasing. Often it is desirable for an organization to use a lighting management company if it does not have the proper equipment and trained staff to maintain the system properly itself.

Planning Factors

The most economical group relamping and cleaning interval must be established. Many factors are involved, so the facilities manager must:

- Establish the maintenance cycle so that there is neither excessive light loss nor wasted equipment.
- Determine the rate at which dirt accumulates in the environment.



Figure 28-2. A fluxometer developed to measure a luminaire's available light in order to determine the benefits of periodic cleaning.

- Evaluate the impact of dirt on luminaires and room surfaces for the specific lighting system.

Several options with factors applicable to the facility should be considered, and results should be compared to determine the best maintenance interval.

In addition, the application also dictates other maintenance requirements. Luminaire accessibility and rate of dirt accumulation vary in almost every circumstance. Planning must take these conditions into account. For example, in many industrial areas, not only is the rate of dirt accumulation high and the dirt dark and adhesive, but the luminaires are usually mounted high up, requiring mechanized lifts to reach them.

Plan Execution. The building's environmental characteristics greatly affect how maintenance is performed. Generally, cleaning and relamping operations require several basic steps:

1. Make the luminaires shock free. Lamp sockets present an electric shock threat to the maintenance

technician. The electrical circuit must be turned off when working on luminaires.

2. Remove the shielding material and lamps. Louvers, lenses, or diffusers in frames can be unlatched for cleaning in place or removed from the luminaire and passed to the technician on the floor. Lamps are then removed and also passed down to the technician, who cleans or discards them.
3. Clean the basic unit. If present, heavy deposits of dirt should be vacuumed or brushed from the reflector or other surfaces. The entire unit is then ready to be washed with a suitable solution utilizing a brush, sponge, cloth, or spray bottle. After washing, the entire unit should then be rinsed to remove any residue of dirt or solution. Indirect luminaires should have the dust and dirt blown out with an antistatic nozzle.
4. Clean the shielding material and lamps. While the reflective surface is being cleaned, the technician on the floor cleans shielding materials. During relamping, the old lamps should be placed in a disposal area, before new lamps are brought in for installation. Plastic lenses or louvers should be dried with a damp cloth. Dry wiping can cause electrostatic charging, which attracts dust. Drip drying can leave streaks on prismatic lenses. Parabolic louvers should be cleaned using ultrasonic machines. Antistatic fluid should be applied to the shielding material, except for glass, to retard dust accumulation.
5. Replace the lamps and shielding material. The clean shielding and new or cleaned lamps are passed up to the technician at the luminaire for installation.
6. Troubleshoot. During the above steps, the technician at the luminaire should check for damaged or defective components and be prepared to replace them with new ones. The lighting system should then be tested and checked for defective lamps, ballasts, sockets, and wiring.

Safety and Environmental Considerations

During cleaning and relamping, the cleaner and the floor technicians should observe all safety precautions. For specific professional safety requirements, consult the U.S. Occupational Safety Health Administration (OSHA) in Washington.

Equipment Disposal.⁶ Replaced lamps and ballasts should be disposed of according to state and federal guidelines. Precautions should be taken when disposing of older ballasts containing PCBs. While the manufacture and distribution of older ballasts containing PCBs were banned in the United States in 1978, they can still be found in older luminaires. A ballast without PCBs is appropriately labeled, "No PCBs." If ballasts containing PCBs are encountered, a lighting man-

agement and maintenance professional, a hazardous-waste treatment professional, or any state or federal organization that offers disposal resources should be contacted. Ballasts containing PCBs must be disposed of in accordance with state and federal guidelines. The U.S. Environmental Protection Agency in Washington can be contacted for more information.

CLEANING COMPOUNDS

Different cleaning applications require different cleaning compounds. Improperly selected or used compounds can scratch or otherwise deteriorate the luminaire surface. For each application, the manufacturer's recommendations should be followed for best results. Several general tips are listed below:

Aluminum. Very mild soaps and cleaners followed by a thorough rinse with clean water prove effective with aluminum. Strong alkaline cleaners should never be used.

Porcelain Enamel. Nonabrasive cleaners can be used on porcelain. Detergents and most automobile and glass cleaners are effective.

Synthetic Enamel. Some strong cleaners may injure this finish, particularly in cases where the enamel is left to soak in the solution. Alcohol or abrasive cleaners should not be used. Detergents produce no harmful effects.

Glass. As with porcelain enamel, most nonabrasive cleaners prove effective. Most detergents work well; after cleaning, however, the lens must be rinsed. Glass reflectors may simply be wiped dry.

Plastics. Plastic should not be dry wiped after application of a rinse solution because this causes the formation of electrostatic charges. Also, plastic should not be drip dried, as this results in streaks. The most effective method of drying plastics is vacuuming. Most common detergents do not provide a high degree of permanence in their antistatic protection. Some antistatic compounds with greater permanence are available.

CLEANING EQUIPMENT

Cleaning, group relamping, and new equipment installation can be performed more efficiently with proper equipment. **Caution:** Proper safety training should be given for all maintenance equipment.

Ladders and Stilts. Ladders are often chosen for their low weight, low cost, and simplicity (Figure 28-3). Safety, mobility, and height restrictions limit their use, however. Aluminum or other conductive ladders must not be used. Wood or fiberglass ladders should only be used if they are OSHA



Figure 28-3. A ladder is used to change a ballast.

approved. Stilts can also be used for maintenance in spaces with relatively low ceilings (Figure 28-4).

Scaffolding. Portable scaffolds are generally safer and more mobile than ladders. Scaffolding provides more room for equipment and firm footing for technicians. Scaffolds generally should be light, sturdy, adjustable, mobile, and easy to assemble and dismantle. The right type of scaffolding often depends on special requirements, such as mounting on uneven surfaces or clearance of obstacles such as tables or machines. In all aspects, the scaffold must conform to OSHA standards.

Telescoping Scaffolding. The telescoping scaffold (Figure 28-5) provides a quick and versatile method for reaching a variety of mounting heights. This equipment, which comes in various sizes, has platforms that can be raised and lowered either manually or electrically.

Personnel Lift. The personnel lift has proven itself as one of the quickest and most efficient maintenance devices (Figure 28-6). The platform is raised and lowered automatically. Some types of personnel lifts can be driven from the platform.

Bucket Truck. The bucket truck (Figure 28-7) is used in many outdoor applications, such as sign lighting, street lighting, and parking lot lighting.

Disconnecting Hangers. Disconnecting hangers allow the technician to lower the luminaire to a convenient work level (Figure 28-8). The luminaire's electrical circuit connection



Figure 28-4. Stilts used for maintenance in spaces with low ceiling heights.

is automatically disconnected for safety. When the luminaire is raised after the work is complete, the hanger positions the luminaire and reconnects the electrical circuit automatically.

Lamp Changers. Lamp changers simplify lamp replacement. They grip lamps either mechanically or with air suction. Lamp changers usually are on a pole and are used from the ground (Figure 28-9).

Catwalks, Cranes, and Cages. These types of equipment can be incorporated as an integral part of the lighting system for servicing (Figure 28-10). They enable luminaires to be maintained speedily and safely. Power to a crane must be turned off before lighting maintenance is begun.

Vacuum Cleaners. A vacuum cleaner is used to remove dust from luminaires. While some dirt can be removed this way, the luminaire should also be washed. The use of a vacuum cleaner is effective for industrial and commercial indirect luminaires.

Ultrasonic Cleaning. Ultrasonic cleaning requires that personnel be adequately trained so that they do not damage the



Figure 28-5. Telescoping scaffold.

surfaces. This method removes dirt and dust from metals, plastics, glass, and other materials by using high-frequency sound waves. A generator, a transducer, and a suitable tank constitute the ultrasonic cleaning system. The generator produces high-frequency electrical energy, which the tank-mounted transducer converts to high-frequency sound waves. These sound waves travel through the cleaning solution and cause cavitation, the formation of countless microscopic bubbles, which grow in size and then violently collapse. This phenomenon creates a scrubbing action that rapidly and forcefully removes dirt from the material immersed in the solution. Ultrasonic cleaning proves very effective with parabolic louvers. Metallic louvers, however, may be damaged by this method over time. Parts should be rinsed in deionized water after ultrasonic cleaning.

TROUBLESHOOTING AND MAINTENANCE TIPS

Planned lighting maintenance entails more than simply changing lamps and cleaning. It is also an opportunity to efficiently



Figure 28-6. Mobile platform lift.

locate and repair defective or broken components causing system problems. See Chapter 6, Light Sources, for diagrams and explanations of the circuits described in this section.

Caution: Follow manufacturer and government environmental guidelines for proper disposal of lamps and ballasts.

Preheat Fluorescent Lamp Circuits

Troubleshooting

1. Replace existing lamps with lamps known to be operative.
2. Use only lamp types that are listed on the ballast label. Check to make certain lamps can be used on preheat circuits.
3. Replace existing starters with starters known to be operative and of proper rating. Refer to Chapter 6, Light Sources, for a description of the various types and the features of each.
4. Check luminaire wiring for incorrect connections, loose connections, or broken lampholders or wires. Refer to the wiring diagram printed on the ballast.



Figure 28-7. Bucket truck.

5. Check the ballast to see if the label agrees with the application with regard to temperature limitations and lamps. Replace the ballast if faulty or inappropriate.

Maintenance Hints

- Deactivated lamps should be replaced as quickly as possible. Cycling lamps cause abnormal flow current in the ballast, which causes ballast heating and reduces ballast life.
- Lamp cycling also reduces starter life.

Rapid-Start Fluorescent Lamp Circuits

Constant heater current is essential for proper starting of all rapid-start lamps. It is also essential for proper lamp operation.

Troubleshooting

1. If a lamp requires 5 to 6 seconds to start, one electrode may not be receiving the cathode heating cur-



Figure 28-8. Disconnecting and lowering hangers.



Figure 28-9. Pole lamp changer.

rent. This usually produces excessive darkening of that end of the lamp, which is visible after a short period of operation. With lamps removed from the sockets, check heater voltages with available testers. If a voltmeter is used, a 10- Ω , 10-W resistor should be inserted in parallel with the meter. The meter should measure at least 3 V. If proper voltage is found, check for poor contact between lamp holder and base pins or contacts on the lamp. Also check for proper spacing of lampholders. If no voltage is measured, check for open circuits caused by poor or improper connections, broken or grounded wires, or an open heater circuit on the ballast. Verify that the wiring conforms exactly to the ballast label diagram.

2. If one lamp is out and the other lamp is operating at low brightness, or if both lamps are out, only one lamp may have failed. Refer to the circuit diagram in Chapter 6, Light Sources, and note that two-lamp magnetic and some electronic circuits are of a series design.
3. Replace the ballast if the output voltage is not within its rated voltage, or if no voltage is present after determining that the input voltage to the ballast is correct.

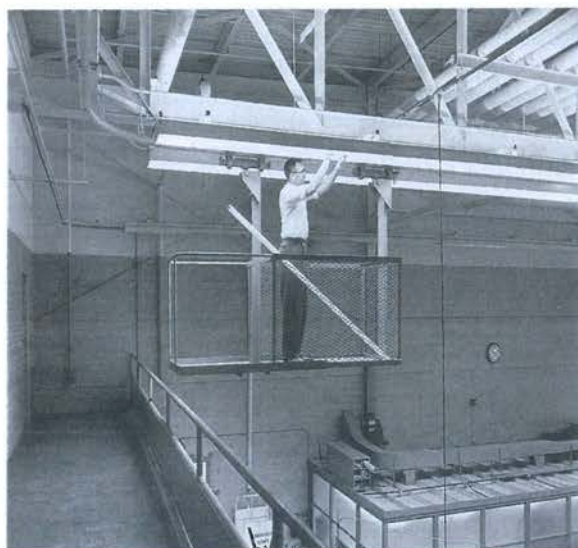


Figure 28-10. Maintenance cage.

Maintenance Hints

- Failed lamps should be replaced as quickly as possible. Rapid-start lamps require both heater current and starting voltage for proper operation. If either is missing, poor starting or short lamp life results. In a two-lamp circuit, one lamp can fail so that the second lamp operates at reduced current. This condition reduces the life of the second lamp.
- Lamps should be kept reasonably clean. All rapid-start lamps are coated with a silicone to provide reliable starting in conditions of high humidity. However, dirt can collect on the lamp surface and then absorb moisture when the humidity is high, thus nullifying the silicone coating and making the starting unreliable.

Instant-Start Fluorescent Lamp Circuits

Two-lamp circuits can be of either lead-lag or series-sequence design. Lead-lag ballasts operate lamps in a parallel circuit, meaning that if one lamp fails, the other should continue to operate properly. Series-sequence ballasts operate lamps in series, meaning that if one lamp fails, the other fails or glows dimly. Some multilamp electronic ballasts for T-8 lamps are of instant-start design. Only the failed lamp is inoperative in this case.

Troubleshooting

1. Replace existing lamps with lamps known to be operative.
2. Check lampholders for broken or burned contacts or discolored plastic in the holders, indicating high temperature. Check circuit for improper or broken wires. Refer to the wiring diagram on the ballast.
3. If the ballast is suspected of being defective, replace it with one known to be operative. Measurement of output ballast voltages in the luminaire is difficult because the primary circuit of the ballast is automatically disconnected when a lamp is removed. Refer to the circuit diagram in Chapter 6, Light Sources.

Maintenance Hints

- Deactivated lamps should be replaced as soon as possible. In a two-lamp series magnetic circuit, one lamp can fail so that the second lamp operates at low brightness. This condition reduces the life of the second lamp and also causes an abnormal current to flow in the ballast, giving rise to ballast heating and a reduction in ballast life.
- Flickering instant-start or "slimline" lamps, which show heavy end blackening, should be replaced, even if the lamps still light. This condition is known as lamp rectification and causes reduced ballast life if it is allowed to persist.

Incandescent Lamps

Troubles with incandescent lamps are usually the result of misapplication, improper operating conditions, or poor maintenance. Apply the hints below to avoid most problems.

Maintenance Hints

- Overvoltage operation. Overvoltage operation drastically shortens lamp life. For example, a 120-V lamp operated on a 125-V circuit suffers a 40% loss in life. Refer to Chapter 6, Light Sources.
- Shock and vibration conditions. Under such conditions, the use of vibration-service or rough-service lamps is recommended. The use of general-service lamps under these conditions results in short life.
- Sockets. High-wattage lamps should not be operated in sockets designed for that wattage, or else excessive lamp and socket temperatures may result. Excessive temperatures may affect lamp performance or may shorten the life of insulated wire and sockets.
- Luminaires. Only the proper lamps for which the luminaire was designed should be used. Contact of any metal part of a luminaire with a hot lamp may result in violent failure of the lamp.
- Cleaning lamps. A wet cloth should not be used to clean a hot lamp. A violent failure may result.
- Proper burning position. Lamps should be operated in their proper burning position as specified by the lamp manufacturer. Operation of the lamps in the wrong position can cause a lamp to fail prematurely.
- Replacing lamps. Whenever possible, lamps should be replaced with the power switched off; otherwise, an arc between the lamp base and the socket can occur.
- Tungsten-halogen lamps. These lamps should always be installed with the power switched off. It is also recommended that the bulb be held with a clean cloth or tissue or gloves to avoid fingerprints that can cause bulb discoloration, reduction in light output, short life, and, possibly, violent failure. Follow lamp manufacturers' instructions on the carton.
- Dichroic reflector lamps. Certain lamps utilize a dichroic reflector designed to radiate heat back through the reflector portion of the bulb. Luminaires using these lamps should be ventilated or provided with adequate cooling of the socket and wiring adjacent to the bulb.

Metal Halide Lamps

Troubleshooting

1. Many metal halide lamps should be used only in specified operating positions, or else short life and improper light output and color will result.
2. The time to restart after a short power interruption can be much longer than it is for mercury lamps.

3. It is normal for metal halide lamps to have a short delay between the time the circuit is energized and the time the lamp starts.
4. Slight color shifts from lamp to lamp are characteristic of metal halide lamps. Also, one to two days of operation may be required to stabilize the color of a lamp and the uniformity among a group of lamps
Caution: Follow lamp manufacturers' recommendations with respect to metal halide lamp operation in open or enclosed luminaires.
5. Replace the lamp with one known to be operative. Be sure the operative lamp is cool, because hot lamps do not restart immediately.
6. Check that the lamp is properly seated and that its base eyelet and shell make proper contact in the lampholder.
7. Check the ballast nameplate. Make sure that ballast and lamp designations match. Refer to the system of lamp and ballast designations developed by the lamp industry and American National Standards Institute (ANSI).
8. Check the ballast wiring. If a multiple-tapped primary-winding ballast is used, be sure the connected tap matches the supply voltage.
9. Check the supply circuit wiring for open circuit or incorrect connections.
10. Replace the ballast if no output voltage can be obtained and make sure that the line voltage is properly connected to the ballast input terminals.
11. If a lamp fails prematurely, especially if it does so repeatedly in the same way in the same luminaire, check for the following:

- a. Cracks or breaks in the bulb. These allow air to enter the lamp and cause arc tube seal failure. They can be caused by rough handling, by contact with metal surfaces of a bulb changer or metal parts of the luminaire, or by water droplets falling on a hot lamp.
- b. Overly blackened or swollen arc tubes. This indicates excessive lamp current and overwattage operation (see items 7, 8, and 9 above). Also, the ballast may have failed due to a component failure, such as a shorted capacitor or core winding.

If the power is lost in an HID ballast-lamp combination for even a few cycles, the lamp extinguishes itself and then has to cool down somewhat, reignite, and warm up again before reaching maximum light output.

Caution: To prevent electric shock hazard, always turn off the power before removing or installing lamps. This is especially important when removing lamps that may have cracked or broken outer envelopes. Unless the power is turned off, the exposed metal parts of the internal lamp

structure are connected to power, and touching them causes an electric shock. Always follow OSHA guidelines.

Maintenance Hints

- If a metal halide lamp is to be moved from one luminaire to another, keep it in the orientation in which it was installed while transferring it. If the lamp is rotated, color can vary.
- Operate metal halide lamps only in their allowed operating positions.
- If multiple-tapped ballasts are used, check to be sure that the tap matches the supply voltage to which the ballast tap is connected. Connecting a given line voltage to a tap marked for a higher voltage gives low light output due to underwattage operation. Connecting it to a tap marked for a lower voltage causes poor lamp lumen maintenance and short lamp and ballast life due to overwattage operation.
- The line voltage should be nearly constant. A variety of ballast types are available that provide an appropriate percentage of lamp wattage regulation with respect to the percentage of line voltage variation.
- Lamp-and-ballast combinations must be chosen so that their electrical characteristics match. This can be assured by following the system of lamp and ballast designations developed by the lamp industry and ANSI. Incorrect matching of lamp and ballast may result in short life and equipment damage.
- Lamps should be handled carefully. Rough handling can cause scratches or cracks in outer glass envelopes, resulting in short lamp life and possible injury.

Caution: Even if the outer envelope of a lamp is broken or punctured, the arc tube may continue to burn for many hours. Turn off the power and replace the lamp immediately. Certain types of lamps are available that automatically extinguish if the outer envelope is broken or punctured.

High-Pressure Sodium Lamps

Troubleshooting

1. Follow steps 5 through 10 listed for metal halide lamps.
2. If lamps fail prematurely, especially if they do so repeatedly in the same way or in the same luminaire, check the following:
 - a. Cracks or breaks in the bulb (see item 11a under "Metal Halide Lamps").
 - b. Excessive discoloration of the arc tube or a metallic deposit on the inside walls of the outer envelope, which may indicate overwattage operation (see items 7, 8, and 9 under "Metal Halide Lamps"). Also, ballast components may have failed; for example, a capacitor or a core winding may be shorted.

3. A high-pressure sodium lamp must be started with an ignitor. If both the old and a known good lamp fail to start, steps must be taken to determine if the ignitor or the ballast or perhaps both are defective. First make certain that the proper line voltage is correctly connected to the ballast input. Obtain a ballast tester or voltmeter, and follow the manufacturer's instructions to determine the defect. Do not connect a voltmeter or multimeter to an open or inoperative high-pressure sodium socket. The high-voltage pulse from the ignitor will damage the meter.

Maintenance Hints

- Follow the third through sixth bullets for metal halide lamps.
- High-pressure sodium lamps have a vacuum in the space between the ceramic arc tube and the outer envelope. Handle these lamps carefully, since vacuum lamps are known to make a loud noise if the glass should break when dropped.
- In case the outer envelope breaks during lamp operation, UV emission is not a problem.

Caution: To prevent electric shock, always turn the power off before removing or installing a lamp. This is especially important when removing lamps that may have cracked or broken outer envelopes. Unless the power is turned off, the exposed metal parts of the internal lamp structure will be live, and touching them will cause an electric shock.

Mercury Lamps

Follow the recommendations and all cautionary measures given for metal halide lamps, because these generally apply to mercury lamps.

Low-Pressure Sodium Lamps

Troubleshooting

1. Replace the lamp with a lamp known to be operative.
2. Check the lampholder for proper lamp seating and contact.
3. Check the ballast nameplate reading for compatibility.
4. Check the ballast wiring. If a multiple-tapped ballast is used, be sure the ballast tap matches the supply voltage at the ballast.
5. Check the circuit wiring for open circuit or incorrect connections.
6. Check the grounding of the luminaires.
7. Replace the ballast.
8. If lamps fail prematurely, check for the following:
 - a. Lamp breakage. Check lamps for cracks or scratches in the outer bulb. These can be caused by rough handling, by contact with metal sur-

faces in the bulb changer or luminaire, or by moisture falling on an overheated bulb.

- b. Bulb touching the luminaire, lampholder, or any hard surface.
9. If the arc tube is cracked, blackened, or swollen early in life, or if the connecting leads inside the outer bulb are damaged, check for the following:
 - a. Overwattage operation. Check the ballast rating, the voltage at the ballast, and whether the proper tap on the ballast is being used.
 - b. Excessive current. Check if the ballast is shorted. Check for possible voltage surges or transients on the supply line.

Caution: Do not replace the lamp until the circuit is checked and the cause of the trouble has been corrected.

Maintenance Hints

- If multiple-tapped ballasts are used, check to be sure the tap matches the supply voltage at the ballast. Low voltage causes low light output, poor lumen maintenance, and reduced lamp life. High voltage causes short lamp life.
- The circuit should be free from voltage fluctuations. Replacement ballasts should match the particular voltage, frequency, and lamp type.
- The proper lamp type should be used for the ballast. Incorrect matching of lamp and ballast may result in short lamp life or lamps going on and off repeatedly.
- Lamps should be handled carefully to avoid breakage.

REFERENCES

1. Finn, J. F. 1973. Servicing: A design priority. *Light. Des. Appl.* 3(9):28-30.
2. Barnhart, J. E., C. DiLouie, and T. Madonia. 1993. *Lighten up: A training textbook for apprentice lighting technicians*. Princeton, NJ: interNational Association of Lighting Management Companies.
3. Clark, F. 1968. Light loss factor in the design process. *Illum. Eng.* 63(11):575-581.
4. Barnhart, J. E., C. DiLouie, and T. Madonia. 1993. *Illuminations: A training textbook for senior lighting technicians*. Princeton, NJ: interNational Association of Lighting Management Companies.
5. Clark, F. 1963. Accurate maintenance factors. *Illum. Eng.* 58(3): 124-131.
6. Clark, F. 1966. Accurate maintenance factors. Part two (luminaire dirt depreciation). *Illum. Eng.* 61(1):37-46.
7. American Society of Heating, Refrigerating and Air-Conditioning Engineers. 1999. *Energy efficient design of new buildings except new low-rise residential buildings*. ASHRAE/IESNA 90.1-1999. Atlanta, GA: ASHRAE.
8. Lighting Research Center. 1992. *Guide to responsible disposal of fluorescent lighting ballasts*. Schenectady, NY: Niagara Mohawk Power Corporation.

Emergency, Safety, and Security Lighting

29

EMERGENCY LIGHTING

The designer faces no greater challenge and, possibly, no more important responsibility than making provisions for reliable emergency lighting. In many situations occupants of a building need to evacuate for such reasons as fire and power failure. These occasions can become dangerous if proper emergency lighting is not available or is inadequate. Therefore, it is the designer's responsibility to provide adequate egress route illumination and informational signage. Likewise, it is the responsibility of building engineers, owners, and property managers to ensure that these systems are properly installed and maintained.

Not every lighting failure is associated with a need for rapid evacuation, and not every evacuation is accomplished without utility power. Nevertheless, emergency lighting is required at all times. Such factors as the presence of smoke, the operation of sprinkler systems, hazards presented by manufacturing equipment or architectural features, and physical disabilities or special needs of building occupants can compromise the effectiveness of simple lighting solutions. The egress lighting system design must anticipate the full range of possible conditions.

Collaboration among the lighting designer, engineer, building owner, occupants, architect, fire officials, and utilities is highly recommended as a means of understanding and planning for the variables that might interfere with the effectiveness of building egress. These variables should be addressed early in the building design stage so that the emergency lighting system can be most effectively integrated with the design of other building systems.

The purpose of this chapter is to provide assistance in identifying these important design considerations and to make emergency lighting recommendations. Several terms are unique to emergency lighting, and definitions can be found in the Glossary.

Many of the recommendations in this chapter also apply to emergency lighting in mines; aircraft, ships, and other vehicles; and outdoor structures such as oil drilling platforms. For more information see Chapter 23, Transportation Lighting, and Chapter 19, Industrial Lighting.

EMERGENCY, SAFETY, AND SECURITY DESIGN ISSUES

Emergency

- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Modeling of Faces or Objects
- Shadows

Safety

- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Surfaces
- Luminances of Room Surfaces
- Modeling of Faces or Objects
- Reflected Glare
- Shadows
- Source/Task/Eye Geometry

Security

- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Surfaces
- Light Pollution/Trespass
- Modeling of Faces or Objects
- Peripheral Detection
- Shadows
- Source/Task/Eye Geometry

Codes and Standards

The designer should become familiar with the applicable codes in the project jurisdiction before designing emergency lighting systems. These codes have been developed through a number of government and private organizations, including the National Fire Protection Association (NFPA), National Research Council Institute for Research in Construction (NRC/IRC, Canada), U.S. Uniform Building Code (UBC),

U.S. Southern Building Code Congress International (SBCC), Canadian Standards Association (CSA), Canadian Occupational Safety and Health Board (COSHA), Building Officials and Code Administrators International (BOCA), Commission internationale de l'Éclairage (CIE) and Underwriters Laboratories (UL), Federal Aviation Administration (FAA), and the Occupational Safety and Health Administration (OSHA). Other sources to consult are Department of Health and Human Services guidelines, local or state board of education requirements, Americans with Disabilities Act (ADA), local fire departments, and fire marshal offices as applicable to the occupancy. Some documents represent guidelines that contain no specific mandates to the designer.

Design Considerations for Emergency Egress Lighting

Illuminance. By itself, illuminance is not an adequate measure of visibility because it refers only to the quantity of light falling on a surface and not the amount reflected back to the eye. Luminance is more closely correlated with visibility (see Chapter 3, Vision and Perception); however, luminance is more difficult to predict and specify for emergency lighting applications. Nevertheless, illuminance does influence the speed of egress from furnished and cluttered spaces,¹⁻⁶ as illustrated in Figure 29-1.⁴ Furthermore, an average illuminance of 0.5 lx might provide sufficient visibility to permit people to exit without colliding with furniture and other obstacles when illuminance distributions are approximately uniform (i.e., $E_{avg}/E_{min} < 2.5$).^{1,3-6}

Some codes and regulations specify average rather than minimum illuminance requirements, as given above. Average illuminance is often meaningless when illuminance dis-

tributions are not uniform to the degree often found in emergency lighting installations. For emergency lighting, minimum illuminance is a more relevant criterion than average illuminance.⁷

The minimum recommended illuminance at the beginning of emergency operation is 10 lx (1 fc) along the centerline of the path of egress and 1 lx (0.1 fc) along a one meter band throughout the means of egress. The maintained horizontal illuminance measured at all points along the means of egress outside the one meter band should be at least 0.5 lx (0.05 fc) whenever emergency lighting is required. In addition, such hazards as steps, curbs, slopes, and obstacles should be illuminated in accordance with Figure 29-2. These values should be increased whenever the effective reflectances of ceiling, wall, and floor are less than 0.5, 0.1, and 0.1, respectively.

Health care facilities require more illuminance in emergency situations to provide life support services to patients. The recommended illuminances for critical care areas should be maintained during emergency situations.⁸

The designer should remember that published isolux (or isofootcandle) distribution curves for directional sources (e.g., incandescent PAR lamps) are typically for a plane perpendicular to the lamp axis. The equipment is usually aimed at angles off the vertical, so the cosine of the angle must be used to calculate surface illuminance. For example, if the lamp is aimed 75° from vertical, the horizontal illuminance is reduced approximately five-fold (i.e., $1/\cos[75^\circ]$).

It is also important to note that zonal cavity methods or point-by-point illuminance calculations are generally not applicable when making calculations for emergency luminaires. Layouts of emergency luminaires are often too widely spaced, and therefore too nonuniform, for these methods to be valid. See Chapter 9, Lighting Calculations, for specific information regarding lighting calculations.

Duration. Occupant evacuation times depend on the size and complexity of the space. Codes specify minimum operating periods for emergency lighting from 30 min to 8 h, with 90 min being the most common. Relevant codes such as BOCA, NFPA, and local codes should also be consulted.

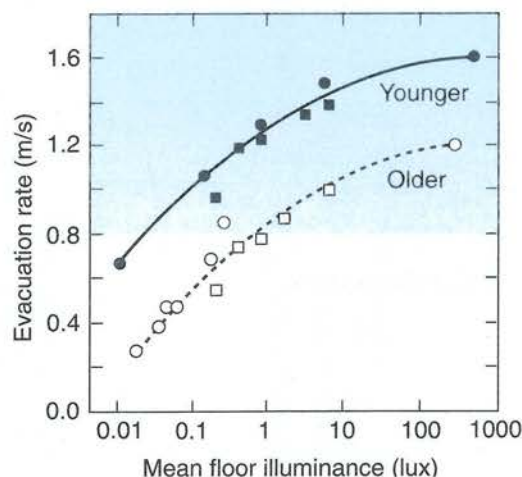


Figure 29-1. Rates of evacuation of both older and younger people in cluttered spaces.

Figure 29-2. Illuminance Levels for Safety

Hazards Requiring Visual Detection	Slight		High	
	Low	High	Low	High
Normal Activity Level				
Illuminance Levels				
Lux	5.4	11	22	54
Footcandles	0.5	1	2	5

These values represent absolute minimum illuminances at any time and location where safety is related to visibility. However, in some cases higher levels may be required (such as where security is a factor). In other conditions, especially involving work with light-sensitive materials such as photographic film, much lower illuminances must be used. In these cases, alternate methods of ensuring safety must be employed.

The designer should also give consideration to extending the operating time if unusual conditions may exist. Such circumstances might include a high occupancy rate by older persons, occupancy by the physically disabled, restaurants, and facilities requiring a long shutdown process.

The light output of battery-backed emergency lighting systems declines during the course of operation. Illuminance levels should be designed so that they do not fall below the required levels throughout the minimum operating period. In the United States, the National Electrical Code (NEC) requires that a minimum of 60% of the initial illuminance be maintained.⁹

Illuminance Uniformity. Minimum uniformity requirements help assure safe and rapid movement along the path of egress. A maximum illuminance ratio ($E_{\max}/E_{\min}$) of 10:1 provides excellent uniformity for safe movement. Ratios in excess of 40:1 can be suitable, but this ratio should be minimized wherever possible. Illuminance uniformity is more easily achieved by using a greater number of luminaires with lower light output than by employing fewer but more widely spaced luminaires with higher light output.

Hazard Visibility. Specification of floor-level illuminance is not adequate for proper illumination of all hazards. All vertical surfaces along the means of egress should be illuminated to assist in defining the escape route. Vertical surface illumination increases the occupant's confidence that obstructions and hazards are visible, and increased confidence contributes to improving evacuation speed. Any area in which a change in direction or floor level occurs along the path of egress can be considered as a hazard area (Figure 29-3). Some examples of such hazard areas are:

- Intersections of corridors
- Abrupt changes of direction of the egress path
- Staircases
- Changes of floor level
- Exits and areas adjacent to exits
- Obstructions along the means of egress

Supplemental Path Delineation. Photoluminescent paints and products can be used to supplement electrical lighting evacuation systems.¹⁰⁻¹⁵ They should not be used as the primary emergency lighting system. They can be applied to hazards, office furniture, baseboards, door frames, stairs, and walls to delineate the egress paths in the event of complete power failure and allow the evacuee to develop a more coherent image of the space. Illumination should be provided to these products over an extended period to keep the photoluminescent pigments activated. Some products require at least 100 lx, 24 hours per day, to remain completely activated, and they vary greatly in terms of luminance and persistence. Materials based on strontium aluminate photoluminescent pigments maintain a brighter level of discharge for a significantly longer period than those based upon zinc sulfide photopigments.¹⁶

Illumination of Fire-Alarm Call Points and Fire-Fighting Equipment. Fire-alarm call points and fire-fighting equipment (Figure 29-4) along the means of egress should be illuminated at all times while the premises are occupied. During emergency lighting conditions, vertical illuminance at these



Figure 29-3. Example of a change in direction requiring an exit sign.



Figure 29-4. This wall-mounted sealed-beam unit provides emergency lighting for fire-fighting equipment (the fire extinguisher) as well as the exit approach that should be kept clear of obstructions (e.g., the barrels shown here).



Figure 29-5. Overhead troffers, some of which are supplied with emergency power, are aligned with the path of egress to more conspicuously delineate the path.

locations should be greater than the immediate surroundings and at least 10 lx (1 fc).

Location and Application of Egress Luminaires. Perhaps the best visual cues for egress come from the egress lighting system itself (independent of signage). It should be designed in such a way that it provides a clear, unambiguous, and conspicuous indication of the egress path (Figure 29-5). Illuminances on the egress path should be higher than those on immediately surrounding areas to help guide occupants to the exits. Similarly, relatively high illuminances near the exit door can make this area conspicuous and quickly identifiable.

Coverage. It is important to provide adequate illumination in all areas that constitute the means of egress. Exit access and discharge areas are frequently difficult to define with certainty, but agreement can and should be reached between the designer and the authority having jurisdiction (AHJ). It is also important to remember that the exit discharge extends outside the building and that luminaires appropriate for outdoor application are required. Many jurisdictions also require emergency lighting and exit marking at all changes of direction of travel, in windowless or underground buildings, and at elevation changes in stairwells or corridors. Locally applicable codes should always be consulted to verify that equipment is provided in all required locations.

Glare control. Inadequate glare control can substantially degrade the value of an emergency lighting system (Figure 29-6). To reduce glare, the designer should specify luminance as well as mounting and aiming angles that minimize glare. The lower the mounting height, the greater the probability of disability glare. Mounting locations and aiming angles should be chosen to position luminaires well off the line of sight to exit signage. Combining the emergency egress luminaire with the exit sign at a single location almost cer-



Figure 29-6. Directional emergency lighting equipment can create disability glare and compromise the efficiency of evacuation. In smoke, luminaires can reduce the visibility of exit signs along the same line of sight.

tainly causes disability glare, and the exit sign will be obscured if the luminaire is aimed at a high angle to the path of egress (Figure 29-6). This also helps reduce the effects of scattered ambient light that would decrease the visibility of signs in the presence of smoke.^{4,17,18} Eliminating competing sources of brightness along the same line of sight also keeps exit signage conspicuous and easy to locate in clear conditions.

Shadows. Highly directional light sources and obstructions, such as partitions or merchandise racks, produce shadows. Body shadows created by evacuees on stairs lighted by a single directional light source are particularly important to avoid. Every flight of stairs should be illuminated by more than one luminaire to minimize shadows on nosings and treads.

Improperly located luminaires can become ineffective if the partitions in open-plan offices create shadows along the means of egress. This problem commonly occurs when partitions are moved to accommodate new office layouts.¹⁹ To minimize this problem, luminaires that are easy to move or provide broad general coverage can help to minimize shadows (Figures 29-7a and b).

Smoke. The possible presence of smoke along the path of egress poses a difficult problem for the designer. The dynamics of smoke vary with the burning materials and conditions in the building. Smoke varies in temperature, color, rate of development, degree of stratification, particulate content, and optical density.^{20,21} All of these properties can hinder the effectiveness of the egress lighting system. See Figure 29-8a and b for an example of the performance of an exit sign in flame and smoke conditions.

Given the inherent variability and instability of smoke, recommendations for emergency lighting during smoke-filled conditions are currently limited. Not all equipment is tested or designed to operate in smoke or fire conditions. However, data and specification do exist on exit sign visibil-

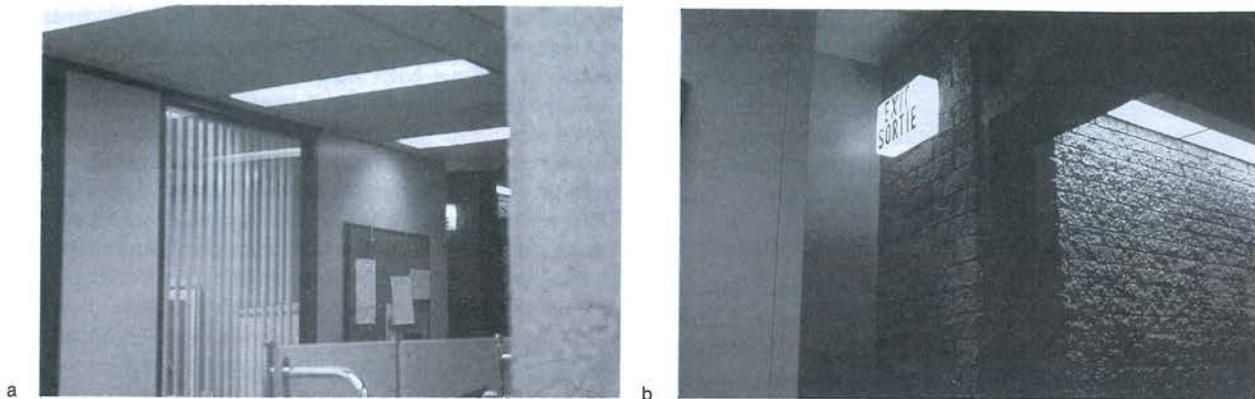


Figure 29-7. a. An exit sign, partially concealed within an alcove formed by a new wall featuring a bulletin board. These photographs (a and b) were taken in a jurisdiction that permits the placement of signs to the left of doors, as in this example. The narrow, obstructed, ill-defined exit route is a problem. Likewise, light from the fluorescent luminaire directly above the sign greatly reduces the visibility of the sign in smoke. b. A close-up view of the sign reveals that the lettering height and spacing between characters are compromised at the expense of visibility, especially when viewed from a distance by a visually impaired person or through smoke, as discussed below.

ity in smoke.²²⁻²⁴ Refer to the section “Design Consideration for Exit Markings” below.

One promising design avenue in this regard is a supplemental lighting delivery system mounted near the floor (see the section “Floor Proximity Path Marking” below). Such systems can light the path while avoiding light absorption and scattering in smoke stratified at higher levels. In addition, such equipment delineates the path for the evacuee

crawling beneath the smoke layer. Pathmarking systems can improve the evacuation speed in smoke-filled conditions.²⁵

Areas outside the egress path. Some codes require lighting outside the egress path. A well-designed emergency lighting system should include illumination in areas that might enhance the safety and functionality of the building during loss of power. Examples of such applications include:

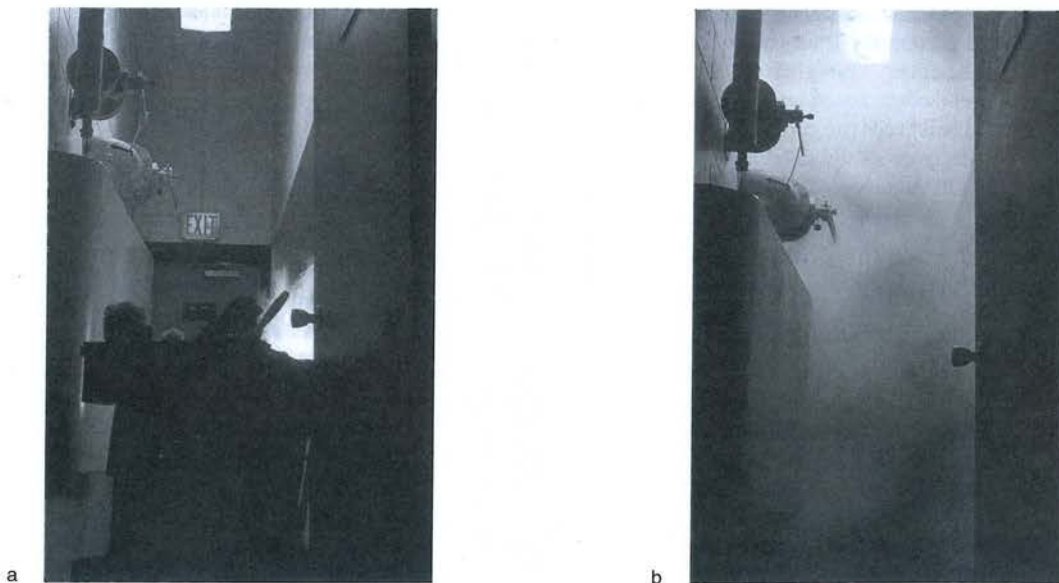


Figure 29-8. a. Exit sign visible in smoke-free fire. b. Exit sign nearly obscured in smoke. Visibility is greatly reduced by the glare from the overhead luminaire.

- Public restrooms
- Generator rooms
- Elevator equipment rooms
- Cold storage rooms
- Computer and communications equipment rooms
- Tool storage and maintenance facilities
- Classrooms
- Manufacturing areas
- Electrical equipment rooms
- Health care facilities
- Hazardous manufacturing equipment
- Underground corridors and other windowless space
- Areas of refuge, areas of rescue assistance

Interiors. In the United States, the Americans with Disabilities Act (ADA)²⁶ prohibits wall objects such as luminaires from projecting more than 10 cm (4 in.) into walks, corridors, hallways, or aisles when these objects are mounted between 67 and 200 cm (27 and 80 in.) above the finished floor. Emergency egress luminaires that are wall mounted, such as compact fluorescent sconces, should be checked for their protrusion into the egress path whenever they are to be mounted within this zone. Exit signs should also be located above the upper limit of this zone. Under the ADA and other state and local codes, the designer should be aware of special areas that might require additional emergency lighting, such as toilet facilities.

Night-light circuits, which are used to provide minimal light during unoccupied times, are commonly used when the designer selects unitary battery equipment or other normally off systems (units that are powered only during power failure) for emergency lighting. The “normally off” systems do not provide egress or ambient illumination when interior luminaires are turned off and the building is occupied by security or maintenance personnel. These night-light circuits need not be part of the emergency lighting system, but as a minimum should meet recommendations for egress lighting.

Ceiling soffits and bulkheads can completely block emergency sources. The designer should coordinate the location of these luminaires with the reflected ceiling plans and confirm with the architect. Minimum ceiling clearances in egress corridors are prescribed by NFPA, BOCA, and ADA. The designer should locate egress luminaires, especially sealed beam lamps, so that they are not obscured by soffits, bulkheads, or suspended luminaires and do not protrude below the minimum headroom set by codes. Supplementary egress luminaires might be necessary if examination of lines of sight along a corridor shows that bulkheads, building signage, or suspended luminaires obstruct the function of emergency egress luminaires and exit signs.

General-purpose luminaires that contain emergency lamps or that are entirely dedicated for emergency lighting should be marked as being part of the emergency lighting system.⁷ These markings, which could be in the form of a red dot or a distinct label, should appear on the exterior of the luminaires so as to be readily apparent. The markings

would help in giving the luminaires priority for maintenance and in giving them due consideration when reorganizing the space.

Exposed unit equipment and central dc systems are not always compatible with the interior design of a space. In addition, certain jurisdictions do not permit the use of concealed emergency equipment such as fluorescent inverters. Other options should be explored for spaces where exposed equipment is not desired. Some equipment, which is manufactured to be concealed behind a ceiling panel during normal operation, releases and energizes the lamps during emergency operation or power loss. Where the appearance of battery-operated equipment or the concealed ceiling panels is objectionable, a generator or inverter system can power selected luminaires that are “normally on” and integral to the lighting system. Any concealed sources should be identified after installation to help ensure that building maintenance personnel know which luminaires provide emergency egress lighting.

Failure of one emergency luminaire should never leave a space in total darkness. In stairwells, alternating a normal source with an emergency source at each landing should provide a reliable system. Emergency egress lighting circuits should not be switched, except where the controls are accessible only to an authorized person as defined by the AHJs or the local codes in effect.

In places of assembly, such as theaters and auditoriums, some jurisdictions permit egress illuminance to be reduced to 2 lx (0.2 fc) during performances or projections but require 10 lx (1 fc) or greater at all other times. Manufacturers of dimming or other control systems can provide an emergency transfer module or contactors to transfer selected luminaires to “full on” upon failure of the normal power source to the dimming control cabinet. In this way the emergency luminaires can become an integral part of the lighting system and function with the nonemergency luminaires. This requires voltage sensing of the source available to the dimming closet.

Exteriors. Most codes enforced by the local AHJ require an emergency “white light” at the exit discharge from a building. This source provides the transition from the interior egress path to the exterior. The exterior source should provide a minimum of 10 lx (1 fc) at the exit. Currently, there is no distance requirement for emergency lighting beyond the exit discharge; however, it is recommended that the transition area from the exit discharge to the exterior areas surrounding the exit discharge be illuminated in accordance with IESNA recommendations for pathways (see Chapter 21, Exterior Lighting). The exit discharge does not always lead to a sidewalk or normal building entrance, but instead leads from a discharge or stairwell directly onto grade. The emergency lighting system used at the exit discharge should be capable of reaching full output within 10 seconds after a loss of power.

Exterior sources should be located either above the door or to one side to reduce glare. Different sources are available

to accomplish exit discharge lighting, and the designer should select the appropriate source for the application.

Incandescent lamps are short lived but can be a good choice when used only as an interim source during high-intensity discharge (HID) lamp restrike times or in a low-voltage dc battery-powered source during power failures. Egress lighting might be required to be on during all times of occupancy, not just during power failures, requiring the use of a battery-powered source in conjunction with a “normally on” source. This normally on source should have long life, as do HID or fluorescent sources. With any power failure, the HID arc extinguishes, so the restrike time must be covered with either a backup instant on lamp or instant restrike lamp.

Low ambient temperatures affect lamp lumen performance of some fluorescent lamps (see Chapter 6, Light Sources). The proper ballast and lamp must be specified for the expected temperature range.

Environmental conditions such as damp, wet, and hazardous locations require the additional consideration of the suitability of the equipment for use in such locations. The AHJs usually refer to the listing or labeling practices of a product testing and certification organization, acceptable to them, in determining the acceptability of the installation. The listed or labeled equipment should be marked for use in these locations.

Partially protected exterior locations under canopies, marquees, and roofed open porches, as well as interior locations subject to moderate degrees of moisture (such as some basements, some barns, and some cold storage warehouses), constitute damp locations. Exterior locations, exposed to weather and unprotected, and interior locations, subject to saturation with water or other nonflammable liquids (such as vehicle washing areas), are classified as wet locations. These locations include roofs near mechanical and elevator penthouses where exit signs are required in some jurisdictions. Locations where fire or explosion hazards might exist due to flammable gases or vapors, flammable liquids, combustible dust, or ignitable fibers in the air constitute hazardous locations.

Normally on exterior luminaires can be controlled by photocells and time clocks to conserve energy during unoccupied periods and daylighted hours. These luminaires can also be controlled by the building energy management control systems, but their circuiting must be kept separate from the building’s normal power circuits.

Many interior and exterior locations require equipment that is safe from tampering and vandalism. Schools and many outdoor locations are examples of applications often requiring vandal-resistant equipment (see Chapter 12, Educational Facilities Lighting, and Chapter 21, Exterior Lighting). In addition, many schools incorporate interior courtyards that are exposed to the weather but totally enclosed by the building walls. These enclosed areas are often required to contain a path of egress back into the building. The entrances from the courtyard into the building should be

marked with appropriately listed exterior location exit signs. The doors from the building into the courtyard should not be marked with exit signs unless the courtyard is specifically designated to be an area of refuge or rescue assistance. Close coordination with the AHJ, owner, and architectural team is required in these special cases.

Emergency Lighting Equipment

Unit Equipment. Unit equipment consists of a self-contained rechargeable battery, a battery charger, a battery status indicator, a transfer device, a test switch and pilot lamp, and provisions for either integral or remote lamps or both. This equipment charges a battery when normal ac power is available and transfers battery power to the emergency light source during a power failure. These luminaires operate only during normal power failures. Both halogen and incandescent sealed beam types and a variety of low-voltage lamps and reflector combinations are used as sources in these luminaires. Most unit equipment operates at 6 or 12 V dc, with the higher voltage preferred when remote lamps are used. Other voltage systems are becoming available.

Unit Inverter. The fluorescent lamp unit inverter system consists of a self-contained rechargeable battery, a dc-to-ac or high-frequency inverter, a battery charger, a transfer device, a pilot lamp, and a test switch. During a power interruption, it operates one or more fluorescent lamps from an internal battery by converting dc power to ac power at a frequency of 60 Hz or higher. When the power is returned, battery charging occurs.

Fluorescent lamp unit inverter systems operate the luminaires used for general lighting in a building. Most units fit into the luminaire ballast channel (Figure 29-9). High temperatures in this space can shorten the life of the battery. An externally mounted system should be specified if high temperatures are expected.

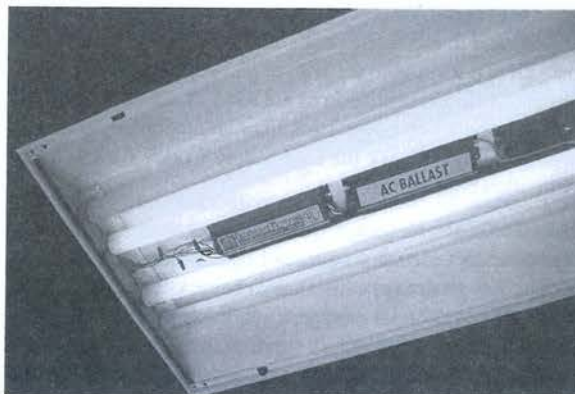


Figure 29-9. An example of a battery-inverter unit mounted in a suspended fluorescent luminaire adjacent to the ballast.

With fluorescent lamp unit inverters, the required test switch and pilot light should be easily visible. Some manufacturers conceal the test switch and pilot light behind a diffusing panel, making these items less apparent for performing maintenance and identification.

The combination of unit inverter and lamp should also be compatible. Inverters that accommodate different lamp types provide different lumen outputs that can be a low percentage of the initial lamp lumens.

Central dc Systems. A normally off central dc system contains a battery, a battery charger, a test switch, a transfer device, and a pilot lamp. The system powers remote incandescent lamps and dc lamps in exit signs during a power interruption. Normal emergency supply voltages are 12-, 24-, and 120-V dc. Other systems using 32, 36, and 48 V still exist.

Lamps for dc systems can be any filament lamp of equal voltage rating. However, most commonly available 24-, 32-, 36- and 48-V lamps are designed for applications other than emergency lighting and should be reviewed for life, lumen output, and future availability.

Central Inverter Systems. A central inverter system contains a battery, a battery charger, a dc-to-ac inverter, and a transfer means, plus appropriate test and monitoring equipment. The system incorporates electronic devices to convert battery dc voltage to 60-Hz line voltage. Standard transfer systems (those with transfer time over 8 ms) can operate incandescent and fluorescent lamps without significant off time. Fast-transfer and uninterruptible power supplies (UPS) can operate HID sources that need a transfer or "off" time of 4 to 8 ms or less. These supplies can also power fire-alarm systems and other crucial 60-Hz equipment. UPS that are selected for emergency power should comply with the applicable codes and standards for emergency power; those that are intended only to maintain computer operation might not be suitable for operating emergency lighting loads.

Standby Generator. The standby generator includes a starter battery, a battery charger and a transfer means, plus test and monitoring equipment. An engine generator produces 60-Hz line voltage. This kind of system powers incandescent and fluorescent lamps and other 60-Hz life safety loads. It is not suitable for HID unless supplementary incandescent or fluorescent sources are used. A standby generator system provides ac power backup as an emergency source in large buildings. Check the Life Safety Code²⁷ for the maximum allowable startup time.

Batteries. The emergency lighting power systems described above use batteries as a source of backup power, except for the standby generator, which uses a battery for engine cranking. Most commercial emergency lighting systems are available with a variety of battery types.

A battery consists of one or more connected cells. Batteries used for backup power are rechargeable or "secondary batteries." The three categories of rechargeable cells in emergency lighting systems contain lead-based plates with

an acid electrolyte, nickel metal hydride with an alkaline electrolyte, or nickel-cadmium with an alkaline electrolyte. The major groups of commercially available cells are lead-acid, lead-calcium, lead-antimony, nickel-metal hydride, and nickel-cadmium cells.

All batteries except nickel-metal hydride can be manufactured as wet type (with liquid electrolyte), and most have a means for adding water; that is, they require maintenance. Also in production is a sealed type (starved electrolyte or gelled electrolyte) that is said to be "maintenance-free." The advantages of sealed cells are that they are easy to ship and virtually eliminate the chance of injury from electrolyte splash. However, sealed cells have shorter life than well-maintained wet cells. Wet lead-based cells offer greater plate thickness and a mid-range specific gravity, both indicators of longer life. Wet cells are normally used for large-power applications where trained maintenance personnel are responsible for their maintenance.

Automobile batteries have different recharge characteristics than those for emergency applications. Automobile batteries last only approximately six months on an emergency battery charger and therefore should not be used as replacement equipment.

Lead-calcium batteries are best suited for controlled temperature environments. They are usually tested at 25°C. Colder temperatures can improve their life but reduce their performance. At elevated temperature, both life and performance are reduced.

Nickel-cadmium batteries withstand elevated temperatures much more easily. Different types are required for various temperature ranges.

Lead-based cells and, to a lesser extent, nickel-cadmium cells emit hydrogen gas during charging and discharging. Sealed cells also provide blowout vents in case severe overcharging occurs. The worst-case hydrogen emission information on large battery installation should be checked to determine whether special ventilation (e.g., exhaust) fans are needed to avoid hydrogen buildup, which can cause explosions.

Batteries are classified as short-, medium-, and long-discharge types. A 90-min operating time corresponds to a medium discharge rate. Equal initial ampere-hour ratings do not mean equal battery capacities. Available amperes at a specific time are the only way to compare battery performance. Manufacturer information should be reviewed before a battery is chosen. Data for discharge rates and operation times provided by battery manufacturers represent ideal-temperature performance under the most favorable charging and discharging conditions. A safety factor should be added to compensate for conditions other than ideal.

The battery must be compatible with its charger, and it must operate efficiently in the application temperature range at the expected maintenance intervals. In addition, the battery must meet all load requirements. UL-924²⁸, from Underwriters Laboratories, and C22.2 No.141-1985,²⁹ from Canadian Standards Association (CSA), allow the battery to

reach 87.5% of nominal voltage for maximum current capacity. In no case can the discharge time be less than 90 minutes in the United States and 30 minutes in Canada.

Because batteries are perishable, and because the time between manufacture and installation can be substantial, shelf life and no-load recharge intervals are important. For long intervals without charging after system installation, it is best to disconnect the battery to prevent deep discharge and then give boost charges at the recommended intervals. The following precautions should be carried out when installing new batteries:

- Store batteries in coolest area prior to installation.
- Check for shipping damage, leaks, dents, cracks, post damage, and post corrosion.
- Check tabs or posts for bends or separations from battery case.
- Verify that the battery is suitable for the environment in which it is installed.
- Check luminaire wiring to and from the battery for corrosion, frays, and insulation integrity.
- Determine when normal building power will be functional and not interrupted.
- Connect batteries only after normal building power is continuous.
- If wet cell, check specific gravity and electrolyte levels.
- Install in proper orientation if a sealed battery.
- Install according to manufacturer's instructions.
- Record the installation date and put the date on the product.

All batteries require maintenance, including so-called "maintenance-free" batteries, which, in this regard, differ only from other batteries in that there is no access to the electrolyte. Most batteries have rapid output decline without warning as they reach end of life. Inspections should therefore be made at least semiannually or quarterly depending on the application, ambient temperature, area humidity, and installation altitude. The following precautions should be carried out when maintaining batteries:

- Perform visual inspection; check for leaks, cracks, and corrosion.
- Check battery terminals for corrosion and clean if necessary.
- Check wet-cell battery vent caps for blockage and clean if necessary.
- Check electrical connections; tighten hardware where necessary.
- Check integrity of anticorrosive gels and add more if needed.
- Check specific gravity and electrolyte level on wet cells.
- Check wiring to and from battery for corrosion, frays, and insulation integrity.

- Check the cells closest to the positive terminal in multicell banks. The most positive cell of the battery takes the greatest electrical strain; it is the best indicator of a battery's condition.
- Check and record ampere and voltmeter readings at all charge rates.
- Use built-in electronic monitor testing if available; check self-diagnostics.
- Check electronic monitor for correct operation.
- Manually test and record battery operation; recharge should be about five times longer than operation time.
- Recognize battery type and normal life expectancy; check installation date and if product is supplied with a replacement date; replace if close to end of rated life.
- Replace only with same type and ampere hour rated battery; most chargers are factory set for specific batteries.
- Record the maintenance date, and keep the date with the maintenance log.

Chargers. Battery chargers for emergency lighting systems must conform to applicable safety standards.^{28,30} This ensures that the combination of battery and charger has met the time requirements for the initial charge and recharge and that the charger has passed nationally established safety requirements.

Most wet nickel-cadmium and lead-type batteries use a two-rate charge: a high current for initial charge and a float (constant-voltage) or trickle (low-current) rate to maintain the battery at maximum capacity. The time needed to recharge depends on the charger's current-producing capacity and the battery's ability to accept that current. A fast recharge requirement can shorten battery life. If the current supplied is too great, the heat created causes a subsequent loss of electrolyte. Battery charging tolerances are critical. Even a slight increase in float voltage significantly reduces the battery life through overcharging; even a slight decrease reduces total capacity through self-discharge. Stand-alone chargers can require field adjustments for best operation. Nickel-cadmium designs use constant-current-charging techniques. These chargers are not interchangeable. For example, a 12-V nickel-cadmium battery has a different charge set point than a lead-cadmium battery.

Light Sources. Incandescent lamps used in normally off emergency lighting applications (Figure 29-10) differ in design from those used for general illumination. These usually have a lamp life of approximately 50 hours and provide significantly more lumens per watt than their longer-lived general-illumination counterparts. Typical types include sealed-beam incandescent, sealed-beam halogen, and miniature incandescent and halogen. These high-output lamps are particularly useful when operated from unit equipment and central low-voltage dc systems.



Figure 29-10. An emergency lighting unit powered by a remote source.

Emergency lamps used in normally on applications should have high reliability and long life expectancy. Maintenance of normally on emergency lamps is essential to ensure their availability during a power failure. Because of their short lives, general-illumination incandescent and halogen lamps are not good choices if an inverter or a generator is the emergency supply. Emergency lamps that are normally on should be less susceptible to filament damage from vibration, have long life, operate over a wide range of temperatures, have good socket contact, and have short (less than 10 s) restrike time. If general-illumination lamps are required for emergency lighting, the physical and electrical characteristics of candidate lamps should be checked to ensure reliability.

Compact fluorescent lamps (CFLs) have become common in emergency applications. These lamps offer long lamp life, high color rendering characteristics, and high efficacy to reduce the power requirement. It is often easier to achieve good illuminance uniformity and low glare with such lamps, because luminaires utilizing them provide wide coverage. The designer should be aware that low-temperature, high-temperature, or high-humidity exterior applications might not be suitable for these lamps, and the manufacturer should be consulted for assistance with such applications (see Chapter 6, Light Sources).

Square-wave inverters for emergency power should not be used with high-power-factor CFL ballasts. The ballast can trip the circuit breaker because its power-factor-converting capacitor can behave like a short circuit to the square wave output of the inverter.

HID lamps are generally incompatible with conventional emergency power sources such as dc systems, generators, or

ac inverters. None of these systems maintains lamp operation during transfer from normal to emergency power, so the long cool-down and restrike times prevent emergency lighting from being available within the 10 s required by the Life Safety Code.²⁷ Fast-transfer and uninterruptible ac inverters are available to prevent this problem and are the only emergency power sources compatible with HID lamps. "Instant-restrike" HID lamps are available, as are systems that incorporate incandescent lamps during HID off periods. If HID sources are selected, the designer should be sure that the spectral characteristics of the source do not degrade the color appearance of exit markings.

Linear fluorescent lamps are also used in emergency lighting systems, particularly for illuminating paths of egress, and in normally on systems. They are used in conjunction with unit inverters, central inverters, or standby generators.

Floor Proximity Path Marking. These systems typically consist of photoluminescent materials, tritium, electroluminescent, LED, or incandescent lamps, which provide a visual delineation of the path of egress during emergency situations. These systems may be activated by fire alarm or loss of power. Available power sources are dc batteries, central inverters, and standby generators. Several path marking systems designed for use in smoke are available. These systems are covered in the Life Safety Code²⁷ and may be mounted in the floor or on the wall nearby. Some states, such as California, have considered requirements for such systems, and the designer should remain alert for codes adopting this emerging technology, keeping in mind that it is a supplementary rather than an alternative emergency lighting system. In the meantime, applying such systems may result in enhanced safety. For more information see the section "Supplemental Path Delineation" above.

Design Considerations for Exit Marking

Legibility and Visibility of Exit Signs. The legibility and visibility of exit signs are determined by three primary factors: sign characteristics, observer variables, and environmental conditions. Sign characteristics include sign luminance, contrast, color, uniformity, graphics, and location. Observer variables include adaptation state, visual capacity, expectations, and familiarity with the space. Environmental conditions include viewing distance, sign position, ambient illuminance, veiling luminance, veiling reflections, glare, competing graphics, colors, and contrast of the surroundings. These factors do not affect visibility equally.

Sign Characteristics

Graphics. Both NFPA 101²⁷ and UL-924²⁸ specify the following criteria for exit sign graphics with a minimum 152-mm (6-in.) legend height and an increase in proportion based on greater letter height. The word EXIT is specified in the United States, while either EXIT or SORTIE are permitted in Canada.

- Stroke width should be 19 mm (0.75 in.).
- Letter height should be 152 mm (6 in.).
- Letter width should be 50 mm (2 in.), except for the letter "I" in EXIT and SORTIE, which should be 19 mm (0.75 in.) wide.
- Intercharacter spacing should be 10 mm (0.37 in.).
- Optional directional indicator should be a chevron, identifiable from a minimum distance of 12 m (40 ft) and located to the left or right of the word EXIT, consistent with the correct direction of egress.

The requirements in CSA-C860²⁹ are similar, except that character size, stroke width, and the spacing between characters are governed by the ratios specified in Figure 29-11. Wider aspect ratios are required for characters having multiple vertical strokes, including S, O, and R.

Several codes, such as CIE,³¹ ISO,³² and NFPA,³³ have provisions for an optional pictograph for exit markings. Its graphic content contains a human figure exiting through a door.²⁶

Viewing distance. The ability to locate and read an exit sign decreases as the distance between the viewer and the sign increases. The current maximum distance between signs, or between a sign and the exit, is 30 m (100 ft). This translates into a visual angle of approximately 17 min of arc for a 150-mm (6-in.) letter height, and 5.6 min of arc for a 50-mm (2-in.) letter width. Visual angles of this size should be resolvable by those with 20/100 or better vision,³⁴ about 95% of the population,³⁵ although questions remain about which features of the word EXIT constitute the critical detail necessary for recognition.

Luminance. Sign luminance is not directly specified by the Life Safety Code²⁷ nor by the National Building Code of Canada.³⁶ The Life Safety Code does state that exit signs that are externally illuminated shall have a minimum contrast of 0.50 and an illuminance of 50 lx (5 fc). Internally illuminated signs are required to be tested by an independent testing laboratory to determine compliance with the requirements in UL-924.²⁸

In other codes, specifications are given for sign luminance. UL-924,²⁸ for example, specifies two methods for

making comparison. One method is to measure the minimum luminance levels and uniformity ratios on the exit sign; the other method involves the testing of the exit sign at 30 m (100 ft), under various external illuminance conditions (on the sign and visual task area) using human observers. UL-924²⁸ and the NFPA Life Safety Code²⁷ presently allow an exception to this requirement for self-luminous and electroluminescent signs that have a minimum letter brightness of 0.2 cd/m² as long as they are placed at their rated and marked viewing distance as determined by an independent testing laboratory. Research, however, has shown that these signs are significantly less visible than signs meeting the 50 lx standard.^{23,37} The CIE specifies a minimum luminance of 15 cd/m² and a maximum of 300 cd/m² for pictographs,³¹ while a United States Aeronautics and Space code specifies 89 cd/m² as a minimum.³⁸ In Canada, the CSA-C860²⁹ luminance requirements depend on the luminance uniformity ($L_{\max}/L_{\min}$) within each letter of the legend and its background when illuminated (Figure 29-12). In addition, all designated points on the sign shall be no less than 8.6 cd/m² when illuminated.

A preponderance of research has demonstrated that increasing sign luminance can increase visibility and conspicuity in both clear and smoke conditions.^{23,37,39-44} There does not appear to be an upper limit for effective sign luminance in smoke.^{22,45} The existence of an upper limit for clear conditions remains uncertain. Some very low wattage exit signs such as LED, although mandated by certain energy codes, in effect can be significantly less visible than compact fluorescent or incandescent signs of higher luminance.

Contrast. The contrast between an exit sign's graphic and its background is very important in determining its visibility. The contrast can be calculated with the formula

$$|L_t - L_b|/L_b$$

Figure 29-11. Exit Sign Typography Requirements from CSA-C860²⁹

Relationship	Letters	Ratio
Strokewidth: Intercharacter spacing	All	$\leq 2:1$
Strokewidth: Interline spacing (e.g., when the words EXIT and SORTIE are each on a separate line)	All	$\leq 2:1$
Character height: Character width	E, T, X	$\leq 3:1$
	S, O, R	$\leq 2.6:1$
Character width: Strokewidth	E, T, X	$\geq 2.6:1$
	S, O, R	$\geq 3:1$

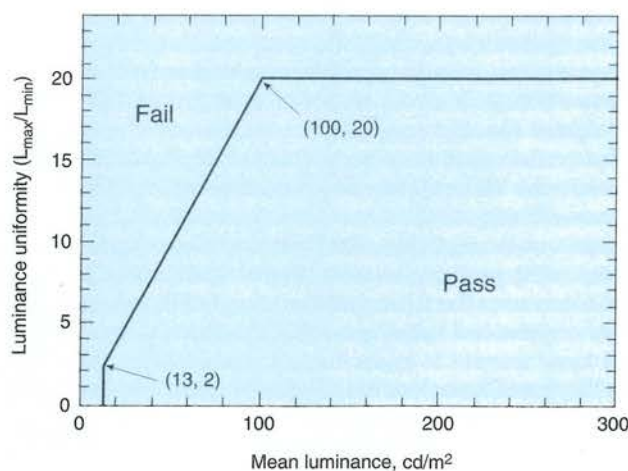


Figure 29-12. Exit sign luminance requirements from CSA-C860.

where L_t is the luminance of the character and L_b is the background luminance. NFPA-101²⁷ and UL-924²⁸ specify that an exit sign must have a minimum contrast of at least 0.5 when measured in darkness. CSA-C860²⁹ requirements are similar to U.S. standards for exit signs having both luminous legends and luminous backgrounds. When either field is opaque, the contrast shall be at least 0.25 with a vertical ambient illumination of 50 lx on the sign face. Ambient lighting can significantly reduce sign contrast by disproportionate reflection from the opaque and luminous fields. For edge-lighted signs, the CSA standard requires contrast of at least 0.25 with 50 lx vertical illuminance on the sign face and with a white nonspecular backdrop ($p = 80$ to 90%) behind the sign. Further, the contrast of edge-lighted signs should be at least 0.5 in darkness and with a black nonspecular backdrop behind the sign ($p = 0$ to 5%). Available research indicates that increasing contrast beyond these minimum requirements can increase sign visibility.^{23,46}

Color. Neither NFPA nor UL provide specifications for exit sign color, although many local jurisdictions do. Color combinations are typically some combination of red or green letters on a contrasting background (often white), although the letter and background color can be reversed. The National Building Code of Canada calls for red letters on white, or the reverse. In other countries, codes specify green and white for exit signs.^{31,32,47} Research on the visibility of exit signs of different colors has been somewhat inconclusive,^{23,37} possibly because contrast or luminance often varied with color. When these factors were held constant,⁴⁵ it was found that color had a negligible effect on sign visibility when compared to the much stronger influences of luminance, contrast, and size.

Configuration and uniformity. Other sign factors that determine visibility include the configuration and uniformity of the sign. Recent research has hinted that stencil-faced signs, in which the letters are illuminated and the background is opaque, can be somewhat more visible in both smoke and clear conditions.^{15,30,33} Sign uniformity has not been studied systematically enough to provide reliable luminance ratios, although some have suggested variations of no more than 3, 4, or 5:1 above the average level over the brightest area of the sign. An Australian standard specifies ratios of no more than 4 or 5:1 for internally lighted signs,⁴⁷ while the CIE suggests no more than 10:1.³¹ Excessive nonuniformity can lead to obscuration of letters or critical details on the sign. CSA C860²⁹ permits ratios of up to 20:1, depending on sign luminance (Figure 29-12); UL-924²⁸ is similar except that it permits ratios of up to 20:1 for each letter or directional indicator and 50:1 for the entire sign.

Observer Characteristics. Physical disabilities in the population must be considered. For example, between 0.5 and 1% of the population can be considered legally blind,⁴⁸ even with corrective lenses. Approximately 8 to 10% of the male population suffers from color vision defects, which can result in inability to see saturated reds, or to confuse colors

such as yellows and greens.⁴⁹ Other observers might suffer mobility impairments that lead to longer egress times. All observers suffer from problems due to changes in their adaptation during the first several seconds after the building lighting is extinguished. For example, normal building illuminance levels can range from 100 to 1000 lx (10–100 fc) or more for offices. The time to adjust to emergency lighting varies with the level of the emergency lighting; the lower the level, the longer the time for adaptation. For example, it takes over 2 min for foveal dark adaptation from an initial adaptation luminance of approximately 300 cd/m².⁵⁰ As a result, signs of very low luminance, such as self-luminous or electroluminescent signs at 0.2 cd/m², might be invisible during the early stages of a power failure or similar building emergency.² Beneficial effects have been reported from using photoluminescent markings and signs under such conditions.^{13,14}

Location and Application of Exit Marking Equipment.

Exit signs are required in all buildings. Exit signs should be located along the required means of egress and at all exit doors or access areas. Directional exit signs should be located at changes of direction in the egress path. Entrances to egress stairs should also be indicated with exit signs.

Exit signs are usually mounted above exit doors to allow passage beneath, and no lower than 2 m (80 in.) above the finished floor to the bottom of the sign. Signs must be visible over the heads of others located in the path of egress. Exit signs should not be more than 30 m (100 ft) apart along the egress path at each exit door,²⁷ at each change of direction, at entrances to stairwells, and at changes of elevation. Check local codes for other required locations. During a fire emergency, smoke can obscure signs mounted above doors (Figure 29-8). One solution has been the use of supplemental floor proximity signs, located approximately 200 mm (8 in.) above the floor (Figure 29-13). These signs are intended to be visible to a person crawling along the floor, just below the smoke.⁵¹ Recent research suggests that such signs should have high luminance, because low-luminance signs are obscured very rapidly in smoke.^{22,23,37} Some incandescent and many exit signs have low sign luminances. The designer should be aware that certification or listing by a recognized agency does not ensure proper application of an exit sign.

The same types of problems are encountered with positioning exit signs as with locating egress luminaires. Ceiling soffits and bulkheads can block the line of sight to exit signs (Figure 29-14). Other types of luminaires, such as surface and suspended linear, can block the view of the sign. Hindrances to proper location and mounting of exit signs are very large doors, glass above doors (Figure 29-7), insufficient recessing or surface mounting depth to mount exit signs above doors, business signs, and emergency egress luminaires. Some exit signs with battery packs are four or more inches deeper than nonbattery types, making them extend lower into the corridor headroom or door opening space. The location of LED exit signs should be checked for



Figure 29-13. Supplemental exit signs mounted near the floor can be seen by occupants crawling along the floor in smoky conditions.

viewing angles, because some of these signs can be less visible when viewed from oblique angles. All diffusing lenses used with LED matrix signs reduce luminance, some more than others. Emergency egress luminaires can produce sufficient glare to obscure the exit sign. Competing light sources and building finishes can also interfere with sign visibility by changing sign contrast, reflectance, and brightness. In exterior applications, certain light sources might not be suitable; electroluminescent signs, for example, are affected by high humidity. Also, incandescent sources can be affected by high vibration, which can damage both the source and the socket.



Figure 29-14. A ceiling soffit can block the line of sight to an exit sign.

Choice of Exit Marking Equipment. Although exit marking equipment is controlled by many regulations, many different products meet the legal criteria. Therefore, specifiers have a large selection of equipment from which to choose.

Options for exit signs include flashing, possibly combined with audible signaling. These options alert the visually-impaired via sound and the hearing-impaired via flashing. The UL-924 standard specifies the on-off duty cycle times for these accessories.²⁸ Some local codes require exit signs with these options to interface with a fire-alarm system as a way to provide additional information to the occupants. Again, local codes should be consulted for facilities that require these options.

Self-contained signs. Self-contained illuminated exit signs maintain sign luminance during normal power loss without the need for an external power source. Battery, battery charger, and transfer systems stay ready to sense power failure and switch to battery backup.

Remote-powered signs. Unit equipment, dc systems, inverters, and generators are all sources of emergency power for remote-powered exit signs. With unit equipment or dc systems, a separate circuit feeds directly to the exit to power emergency lamps. In these systems, the emergency lamp voltage must match the supply. Inverters or generators used as emergency power sources should continue to operate the normally on lamp without the need for additional circuits.

Because remote-powered signs do not contain a dedicated battery and charger, they are less expensive than self-contained signs. The total system cost depends on the remote power source, the distance from that source, and the voltage needed to power the sign. For example, an inverter- or generator-powered system using the same electrical distribution system as that for normal power adds no cost, but dc power needs additional wiring from the emergency source.

Exit Sign Lamps. Long-life lamps are essential for both safety and economical maintenance. A building emergency can occur without immediate power interruption. Therefore, the normally on exit source should be designed for high reliability and reasonably long life.

Many incandescent exit signs have extended-life normally on lamps and low-voltage emergency lamps that operate at the battery voltage. The burn cycle for the battery-operated incandescent lamp or lamps is short, and therefore a short-life, high-lumen-output source can be used. Incandescent lamps provide extended life and lower light output when operated below their rated voltage. Long-life incandescent lamps designed for exit applications have a rated life ten or more times that of standard lamps and still provide needed exit luminance. One advantage of filament lamps is that they can be easily circuited to flash within the specified duty cycle. High-voltage long-life lamps have thin filaments, so shock and vibration can be a problem. Vibration can also cause screwbase lamps to back out of the lampholders. Lamps with a dc bayonet base or fluorescent lamps should be considered for such applications.

Fluorescent lamps are popular choices for exit signs. Low-wattage tubular and compact types are reliable, have high luminance and good luminance uniformity, have a reasonably long life, and are more efficacious than incandescent sources. Total efficacy calculations for fluorescent sources should include ballast loss, which can be as much as 50% of the listed lamp wattage. The power factor is usually low for compact fluorescent lamps and must be considered in circuit sizing. The luminous output of fluorescent lamps depends upon temperature, so care should be taken to avoid excessively high or low temperatures. See Chapter 6, Light Sources for additional details.

Electroluminescent lamps operate between 80 and 200 V ac, require less than 1 W of power per exit face, and yield a uniform luminance pattern. Light is produced by phosphors serving as a dielectric between a conductive foil or metal-sputtered back electrode and a clear front electrode. Lamp life can be 5 years or more when operating at a low frequency and low power density. Exit signs with these sources operate the lamp at line frequency during normal times. If self-contained, they can switch to a higher frequency and higher light output during emergency operation. These are typically considered low-luminance signs and are not commonly used today.

Electroluminescent lamps decline gradually in brightness over their life. The lamp should certainly be replaced before the luminance falls below the 0.21 cd/m² specified by the Life Safety Code.²⁷ Different types of lamps decay at different rates, and the manufacturer should be consulted for information pertaining to expected lamp life and brightness decay.

Light-emitting diodes (LEDs) use 1 to 8 W per exit face. LEDs are highly resistant to vibration, temperature, and humidity because of their solid-state structure. Proper voltage and current transient protection are necessary to achieve long lamp life and good lumen maintenance. These small point sources are used in an array to spell EXIT in English-language signs, are placed behind diffusing material, or are imbedded in plastic strips within the sign. These lamps also have flashing capabilities and can be circuited to vary in intensity. Viewing angles should be checked when using signs with exposed LEDs because the luminous intensity of the LED varies with the viewing angle. This potential problem is overcome when the light-emitting diodes are placed behind diffusing material. Many LED signs have power factors as low as 0.1.²² This is usually not a problem when connected to the building utility supply, because the low power factor of LED signs is usually leading, rather than lagging. This helps to negate the undesired influences of more common lagging nonlinear loads in buildings. Such compensatory loads might not exist when LED signs dominate an electrical circuit. In these cases, the load on the circuit can become 10 times higher than with an ideal power factor of 1. This is an important consideration when sizing backup power sources and distribution circuits. See Chapter 6, Light Sources, for further discussion on power factor.

LEDs exhibit a brightness decay characteristic in which luminance gradually declines over life. The LED assembly, or lamp, should be replaced before the luminance falls below half of the initial luminance. This can occur in as little as one year or less or take as long as five years or more. This decay depends on the driving circuitry, the type of LED technology employed in the sign, and the manufacturer of the LEDs. For example, overdriving LEDs shortens their life. The claims of 100 to 200 years of life expectancy are for complete cessation of light emissions. Different LEDs decay at different rates, and the manufacturer should be consulted for information pertaining to expected LED life to half light output and the light output decay rate. It is advisable to mark this date on the sign or otherwise record the expected LED replacement date. For units that are put into operation simultaneously, group replacement is more cost effective.

Self-luminous signs depend on the radioactive decay of tritium gas and the resultant electrons striking a phosphor-coated glass tube to produce visible radiation. The published life expectancy of these sources is 10 to 25 yr. As stated in previous sections, the luminance of such signs is very low and decays exponentially. This light source can be useful in explosion-prone areas. Areas that require expensive electrical distribution systems also benefit from this nonelectrical exit sign. These signs must be registered with the U.S. Nuclear Regulatory Commission or the Atomic Energy Control Board of Canada for use and proper disposal at end of life. The designer should make sure that the chance of breakage and exposure to the general public is minimal. In the United States, these signs are required to be placed at an interval not to exceed their marked viewing distance, which can be from 15 to 30 m (50 to 100 ft).

Maintenance Requirements

As with any luminaire, exit signs require periodic cleaning and relamping. Due to their vital need during power failures, prompt relamping and proper lamp replacement are required. Group relamping should be considered as a means of reducing maintenance cost and increasing reliability. Most problems can be prevented if installation instructions and replacement part recommendations are followed.

The following precautions should be carried out when installing exit signs:

- For a battery-operated sign, follow the steps described earlier in this chapter for initial battery installation.
- Avoid prolonged emergency lamp operation during installation. Incandescent lamps for emergency mode operation usually have high light output but short life.
- Verify that the exit circuit cannot be switched off.
- Visually inspect lamps and wiring.
- Record the installation date.

- Verify that directional indicators are oriented correctly.
- Verify that the stencil is oriented properly to spell EXIT or SORTIE.
- Make sure lamps are not in contact with the diffusers.
- Ensure the appropriate number of lamps are operational (some authorities require two lamps in both normal and emergency modes).

A permanent record of all maintenance and inspections should be kept in a log book or computer file for review by the local inspection agency, in compliance with the National Electric Code (NEC), NFPA 70;⁹ National Life Safety Code, NFPA 101;²⁷ National Fire Code of Canada;³² and NFPA 110, Emergency & Standby Power Systems.³³

All self-contained emergency lighting and exit signs, including units with maintenance-free batteries, should be inspected and tested every 30 days or more often. This inspection should include, but not be limited to, depressing the test switch a minimum of 90 s and checking for lamp operation (including remotely mounted lamps) and pilot light operation. Luminaires containing wet batteries should be inspected for electrolyte level in each cell and for electrolyte leakage.^{28,36}

Central systems powered by ac or dc supplies or by maintenance-free batteries should also be inspected and tested at least every 30 days. See the discussion on battery maintenance earlier in this chapter for more information. The system's output voltage, frequency, and current should also be checked against the data on the nameplate, and should be within the tolerance specified when connected to the full emergency lighting load.

Regardless of the source of power, the following steps should be carried out when maintaining exit signs:

- Visually inspect lamps and wiring. Ensure the lamps are suitable for the environment.
- Check installation date and institute a group relamping program if appropriate.
- Inspect light transmitting media for dirt or discoloration and replace with parts approved by the manufacturer, if necessary.
- Verify that the directional indicators are consistent with the egress path after maintenance.
- Record the installation date.

In addition, every 12 months, the emergency lighting and exit marking equipment should be disconnected from the normal ac supply and operated for a period of 90 min or the minimum duration for which emergency lighting is required in the given building. During this test, all emergency light sources should operate continuously. To ensure that the space always has emergency lighting when required, the test should be conducted at a time when the batteries can be recharged before the building is occupied. For large installa-

tions where reliable skilled maintenance personnel are not available, a service contract with a responsible service organization should be provided.

Where the designer anticipates little or no maintenance and inspection, self-diagnostic and so-called "smart" self-testing emergency lighting equipment should be considered. A multitude of smart equipment is currently available. It automatically monitors various vital functions of the equipment and indicates failures via visual and audible indicators. It typically runs an automatic test and diagnostic program at least once each month.

When replacing lamps, batteries, or any other parts, the maintenance personnel must select replacement parts with identical ratings and part numbers indicated on the replacement markings in order to maintain the proper visibility, illuminance, and duration of operation in accordance with code requirements. Field-installed diodes used in series with an incandescent lamp to extend lamp life and reduce power consumption should be avoided in exit signs. The diodes reduce the lumen output of the lamp, possibly affecting the visibility of the exit sign as tested by the independent testing laboratories.

In addition to the above procedures, it is also useful to periodically check the egress path to determine if architectural and furniture changes have rendered the emergency lighting system ineffective. One should check that exit signs are readily visible along the path of egress, and that emergency illuminance levels still are on the path of egress. Many building renovations take place without thought to the emergency lighting system, which results in improperly located exit signs and emergency luminaires.

Emergency lighting should be treated as life safety equipment, for without its proper function, an area can be left in total darkness, causing confusion, collisions with obstacles, panic, and even loss of life.

Exit Sign Retrofits

Retrofit kits are available to convert existing exit signs to more efficient light sources (Figure 29-15). Such efforts to conserve energy should not compromise sign visibility. Likewise, the retrofit kits should not compromise the electrical system. Not all kits are equal in these regards.²² A mock-up with recognized retrofit products installed in a facility's signs can help reduce potential problems. It should be noted that in 1995, UL²⁸ rewrote earlier standards for retrofit kits. As a result, many previously accepted procedures have been eliminated or restricted. One should make sure that the kit's listing is indeed current and recognized by local regulatory bodies.

The following precautions should be carried out when installing exit sign retrofit kits:

- Verify the suitability of the kit for the sign, and check the original manufacturer's recommendations. Some retrofits are UL listed for single face



Figure 29-15. A variety of exit sign retrofit kits.

signs only, and some for ac signs only. Not all can be used for battery backup signs.

- Check that no wire splices are made in the lamp compartment. All supply connections must be made through lampholders.
- Use the proper voltage lamp or lamp and ballast combination.
- Position the lamp for the most uniform luminance on exit face.
- Record the installation date.

LIGHTING FOR SAFETY

Lighting for safety is different from emergency lighting in that it involves ensuring proper illumination to provide safe working conditions, safe passage, and the identification of any hazards or obstructions, indoors or outdoors.

Safe conditions are essential in any areas where there are people, and the effects of lighting on safety must be considered. The environment should be designed to help compensate for the limitations of human capability. Any factor that aids visual effectiveness increases the probability that a person avoids an accident or detects the potential cause of an accident and acts to correct it.

In instances where illumination is associated with accidents, the accidents are attributed to inadequate illuminance or poor quality of illumination. However, there are many less tangible factors associated with poor illumination that can contribute to accidents. Some of these are direct glare, reflected glare, and harsh shadows, all of which hamper seeing and can cause visual confusion. Excessive visual fatigue itself can be an element leading to accidents. Accidents can also be prompted by the delayed readaptation that a person experiences when moving from bright to dark surroundings and vice versa. Some accidents that have been attributed to an individual's carelessness could have been partially due to difficulty in seeing from one or more of the above-mentioned factors. The accidents might have been avoided

through the use of good lighting principles. See Chapter 3, Vision and Perception, for further discussion of factors affecting visibility, and Chapter 10, Quality of the Visual Environment, for discussion of lighting design criteria.

Lighting for safety is a concern that must be addressed in both outdoor and indoor locations. People must be made aware of such hazards such as curbs, steps, sloped walkways, and obstacles in one's path (Figure 29-16). Where the illumination is very low or designed to create a special effect, such as in hotels, restaurants, theatres, museums, art galleries, and aquariums, care must be taken to identify changes in elevation and direction without detracting from the visual effectiveness of the lighting.

The industrial environment presents many special concerns with respect to lighting for safety. Physical hazards are marked according to American National Standards Institute (ANSI) documents.⁵⁴ The color rendering properties of the light source should be considered with regard to the physical hazards present in the particular installation.⁵⁵ See Chapter 19, Industrial Lighting, for good industrial lighting practices.

Illuminances

Figure 29-2 lists illuminance levels regarded as absolute minima for safety alone. They are provided for general guidance and should not be interpreted as regulatory requirements. Consult, also, the local regulations.

To ensure these values are maintained, higher initial levels must be provided as required by the maintenance condi-



Figure 29-16. Adequate safety lighting must be used in spaces with obstructions or changes in direction or level, such as stairwells.

tions. In those areas that do not have fixed lighting, local illumination should be provided during occupancy by means of luminaires that are portable or mounted on material-handling equipment and vehicles.

Other Factors

A visually safe installation must be free of excessive glare and of uncontrolled, large differences in luminances. Appropriate guides to limiting glare and adaptation effects are given earlier in this section in discussions of luminance ratios and visual comfort. Maximum luminance ratios are important in avoiding temporary reductions in visibility because of changes in readaptation when alternately looking at areas of widely different brightnesses. Although the quality and quantity of illumination can be designed for safety in an area, it is necessary to know whether the design meets requirements. See Chapter 10, *Quality of the Visual Environment*.

SECURITY LIGHTING

Security lighting is installed to help create a perception of security and to protect people and property from criminal activities.³⁶ The general principles of security lighting apply to new facilities as well as to facilities being upgraded or converted to new uses. These principles are:

- Integrate light into the total security system and thereby facilitate the effectiveness of other security devices or procedures.
- Illuminate objects, people, and places to allow observation and identification and thereby physically reduce criminal concealment.
- Use illumination to deter criminal acts by creating a fear of detection, identification, and apprehension.
- Reduce the fear of crime for the innocent by enhancing a perception of security.

The reader should understand that security lighting goals may conflict with other lighting design criteria. The designer is responsible for resolving these potential conflicts. It should also be emphasized that security lighting is a segment of a total security system; the total environment must be designed with security in mind, if lighting is to be effective.

Lighting helps protect people and property from criminal activities because of its effect on vision. In public places, good security lighting is designed to help everyone see the space clearly. This can better enable a sighted person to identify and possibly avoid threats that may exist on the premises. The presence of good security lighting can also assist in protecting nonsighted persons from potential criminal activity by making would-be attackers visible to others in the area. To achieve the objectives of security lighting in both public and secure areas, attention has to be given to

both vertical and horizontal illuminances, the uniformity of the illuminance distribution, the effect of obstructions, the reflectances of surfaces, background contrast, the degree of glare, the spectral power distribution of the light source, the interaction with electronic surveillance systems, and the effect on the surrounding area.

Target hardening is a useful concept for determining options and setting deterrent objectives that increase the time, resources, and planning of a perpetrator. Time is the enemy of the criminal; the longer the criminal act takes or the more security elements he has to overcome, the higher the probability he will be deterred. The target is the people or property to be protected, and the security features are the hardening elements. Hardening elements include fences, gates and locks, surveillance personnel and cameras, response personnel, and established policies and procedures for operations and maintenance.

A helpful approach to determining security needs is to study the opportunity and means of probable attackers. Security works to deny opportunity and to increase the level of risk necessary to attack the target.

The extent and type of lighting to be used as part of a security system are determined by several different factors:

- **Crime status of the area.** If the site is in a high-crime area, it is likely that many physical defenses, including lighting, are necessary to maintain overall security.
- **Nature of the site.** The type of facility or business, the hours of operation or access, and surrounding conditions affect the approach to security. Lighting should be integrated into the overall goals for the site.
- **Degree of obstruction.** Landscape design and building configurations should not retard detection and identification of unauthorized persons on premises. The means of lighting should be designed to avoid strong shadows and permit observation of the activities of those that are permitted on the site.
- **Ambient brightness of the surrounding area.** Security elements at one site affect the security elements on adjoining sites. If the illuminances are lower or of lower uniformity at one site compared to adjoining properties, the former may be more attractive to criminal activity.
- **Impact on the surrounding area.** Stray light from a security lighting installation can be considered as light trespass by neighbors. There are also possible safety effects on neighboring roads and railroads due to glare. Where signal lights are used to control traffic on roads, railroads, rivers, or at sea, care should be taken to avoid confusion caused by disability glare directly from security lighting, veiling reflections on the signals from the security lighting, or the identification of the security lighting as a signal. Local lighting ordinances should be consulted

prior to any design work. Mounting height restrictions, source type, wattage limitations, shielding, and other local requirements must be followed.

It should be remembered that lighting cannot guarantee security. Crime occurs in daylight hours as well as at night. Also, as pointed out above, lighting is only one factor in security. Other elements are required for good security, including locks, doors, gates, and detection means such as cameras or personnel.

Security Lighting Applications

Broadly, there are four security lighting applications.

- Lighting for controlled sites, where there are other defenses including access control
- Lighting for public spaces (such as mall parking lots) where people may be present at any time and where there are few or no access controls
- Lighting for single-family dwellings
- Lighting for multifamily residences, where each dwelling unit is a private area with few physical defenses and where "common-areas" exist

The recommended practices of IESNA provide more detailed information and should be consulted when developing a lighting design.

Security Lighting for Controlled Sites. A question to consider is whether to light the space at all. It can be argued that lighting a secure area advertises the presence of something worth taking and hence attracts criminals, so keeping the area dark may be a better approach. However, if criminals are likely to know the area contains valuable materials, then the absence of lighting makes the target more difficult to defend. Thus, the choice of whether to light or not depends on an assessment of risk. If the risk of criminal activity is high, security lighting is essential. If the risk of criminal activity is low, and the target is relatively unknown to persons not familiar with the site, then providing security lighting may be counterproductive, especially in rural or isolated areas. It should be noted, however, that the risk of criminal attack is not the only concern for the designer. Safety lighting is also important, so egress portals and refuse storage areas need to be considered before deciding on a solution. In these cases, motion sensors can be employed.

Security lighting for a controlled area should provide uniform illumination so that anyone moving in or around can be seen easily. Also, the security lighting design should provide enough illumination so that intrusion or attempted intrusion into the area can be detected, and any electronic surveillance devices such as security cameras can operate effectively.

These objectives can be achieved in many different ways depending on the site and the nature of the security system.

The following provides examples of security lighting for some common sites.

Storage yards, large open areas, container terminals. Area lighting is typically accomplished with floodlighting or roadway luminaires on poles 10 m (30 ft) or more in height. The recommended average illuminance on the surface of large open areas is given in Figure 29-17. Figure 29-18 shows a typical layout. As a guide, an average-to-minimum illuminance ratio of 8:1 should be achieved. Luminaire spacing depends on the luminous intensity distribution of the luminaires.

The designer of area lighting normally determines the number of poles, the number and type of luminaires, the wattage and type of lamp, and the luminaire mounting height. If the area is unobstructed by trees, structures, or topography, the choice often is determined by simple economic considerations such as first cost, maintenance, and energy. Although simple economic considerations are important, they must be weighed against the anticipated threat and, in economic terms, potential liability from personal injury, theft, and vandalism. It is usually less expensive to provide good security lighting from the beginning.

If the area contains obstructions, as in container terminals or rail yards, a design utilizing multiple source locations reduces shadows. This is especially true if the luminaires are positioned within the site, between obstructions, and with overlapping light patterns. The reflectances of site materials can also be used to advantage. Light colors on buildings and concrete paving enhance the efficiency and uniformity of the lighting system.

Figure 29-17. Recommended Average Illuminances for Security Lighting

Application	Illuminance, lx (fc)	Notes
Large open areas	5 to 20 (0.5 to 2)	The greater the brightness of the surrounding area, the higher the illuminance required to balance the brightnesses in the space.
Buildings	5 to 20 (0.5 to 2)	Vertical illuminance on the building facade. The greater the brightness of the surrounding area, the higher the illuminance required to balance the brightnesses in the space.
Perimeter fence	5 (0.5)	Illuminance on the ground on either side of the fence.
Entrances	100 (10)	Illuminance on the ground in the inspection area.
Gatehouses	300 (30)	Illuminance on the work-plane in the gatehouse. This lighting must be dimmable to low levels at night so the guard can see outside the gatehouse.

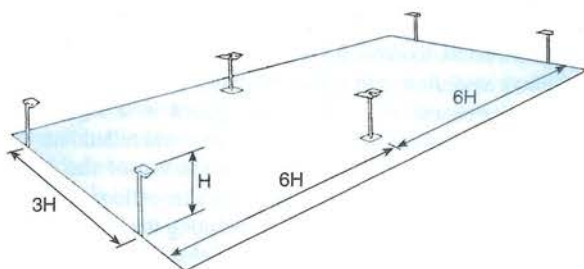


Figure 29-18. Typical layout for floodlighting open areas. H is the pole height to the luminaires.

Disability glare can sometimes be used to protect a secure area by making people outside the protected area highly visible to guards inside the perimeter and making the guards more difficult to detect by people outside. In this system, high-luminance luminaires or strobes are mounted at eye level and aimed outward from the secure area. This technique has a high probability of producing light trespass and light pollution problems. To minimize the duration of these problems, motion sensors can be employed.

Building exteriors. All points of entry to the building and the areas around them should be easily seen. Depending on the construction of the building, the points of entry can consist of walls and roof as well as doors and windows. The most comprehensive approach is to light the whole building, but power density and light pollution concerns limit most security lighting to critical areas of the building and site. The illuminance to be provided on the face of the building is given in Figure 29-17. The ratio between the average and the minimum illuminance on the building facade should not be greater than 8:1. Security lighting for buildings is more effective if the building has a high-reflectance facade and the area adjacent to the building also has a high reflectance (e.g., concrete rather than asphalt).

Critical areas can be lighted by luminaires set in the ground, mounted on the building, or mounted on poles. Ground-mounted floodlights can provide uniform illuminance, but they are very accessible and hence can easily be put out of action. However, for anything other than a basic box-type building, it is difficult to adequately illuminate all of the building surfaces without using an excessive number of luminaires. Pole-mounted luminaires are usually the best option for uniformly illuminating the surfaces of the building and the surrounding area (Figure 29-19). As with any site lighting, light trespass, light pollution, and mounting height restrictions should be considered before beginning the design.

Building interiors. Security lighting for the interiors of buildings depends on the methods of providing security. If security officers are on site or make frequent checks of the location, it is appropriate to have continuous illumination to allow for a quick visual inspection of each space as officers make patrol rounds. If the building is monitored automati-

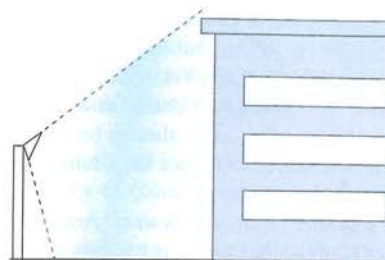


Figure 29-19. Use of pole-mounted luminaires to provide uniform illumination on the area around a building.

cally using cameras, without security officers on site, enough light should be provided to operate the cameras. If infrared motion sensors or infrared camera systems, which do not require light, are used, it is appropriate to design the building to be dark when secure and to be illuminated when trespass is detected by the monitoring equipment.

Perimeter fences and walls. The purpose of lighting perimeter walls and fences is to deter or slow trespass and to enable guards to detect intruders. Perimeter barriers come in several different forms, from masonry walls to barrier plants. The form of lighting used depends on the possibility of seeing through the barrier and whether one or both sides of the barrier is patrolled. If the wall or barrier is solid, there is no possibility of seeing through it. If both sides of the solid barrier are the subject of surveillance, lighting can be provided by positioning a luminaire over the top to reduce shadowed areas at the base of the barrier.

If a view through the barrier is possible, and if the obstruction is patrolled from either inside or outside the secure area, it is useful to be able to see both sides. For this, lighting needs to be provided on both sides. This can be accomplished with a set of pole-mounted luminaires set back from the fence (Figure 29-20). The lighting is most effective if the

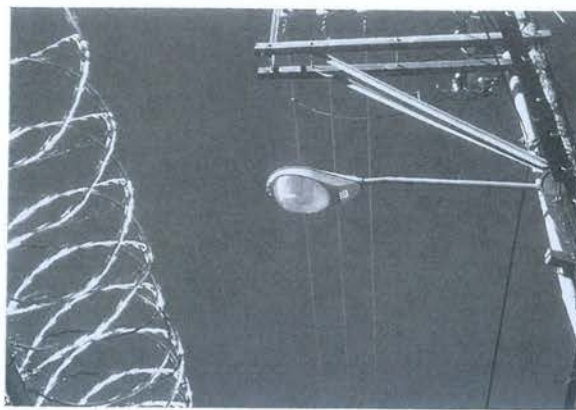


Figure 29-20. Use of a pole-mounted luminaire to light fenced perimeter areas.

luminance of the fence is lower than the luminance of the area on the side being viewed through the fence. This objective can be achieved by using a low-reflectance fence material such as black or dark green coated chain-link. If galvanized chain link is used, care should be taken with the aiming of the luminaires to reduce the illuminance directly onto the fence.⁵⁷

Guarded entrances and gate houses. Access to a secure area is usually controlled by security personnel who stop and inspect people and vehicles entering and leaving the site (Figure 29-21). The entrance should be provided with multiple, redundant luminaires so that the loss of any one luminaire does not seriously degrade the lighting available to the guard on duty.

Luminaires should be located at entrances in order to facilitate inspection of vehicles, vehicle license plates, and vehicle contents, including the driver and the occupants. Good vertical illuminance should be provided to allow for facial identification, inspection of credentials, and receipt of packages without having to use auxiliary hand-held devices such as flashlights. In high-security areas, some luminaires should be mounted at or below pavement level to facilitate inspection of the underside of vehicles. Having a concrete road surface to increase the reflected light helps in the inspection of the underside of vehicles. Backup power supplies should be considered for use during electrical outages.

Illuminance at ground level for the inspection area should be at least 100 lx (10 fc), or twice that of the immediate surrounding areas, whichever is greater. In addition, vertical illuminance equal to 25% of the horizontal illuminance should be provided at the level of the vehicle driver. Good color rendering light sources (CRI > 50) should also be used so that the color of clothing, documents, goods, and vehicles can be easily discerned.

Illuminance inside the guardhouse should be limited to the minimum required for comfortable completion of assigned tasks, such as report writing and equipment use (Fig-



Figure 29-21. Secure entrances must be sufficiently illuminated to enable inspection of visitors or automobiles.

ure 29-17). It should be possible to dim the illuminance in the guard house to allow the guard to see clearly through the windows at night and to limit the ability of those approaching the gatehouse to see what the guard is doing. Well-shielded task luminaires are essential to avoid reflections on any surveillance monitors and the windows of the gatehouse. Fitting the gatehouse with specular-reflecting, low-transmission glass at a tilted angle, painting the inside of the gatehouse in dark colors, and ensuring that illumination can be dimmed all help limit the view into the gatehouse. Figure 29-22 shows a typical installation.

Security Lighting for Public Spaces. The lighting system should make the space look attractive and safe, and hence to encourage its use at night by allowing defensive action at a safe distance. In other words, by enhancing the visibility of people and faces, suspicious or threatening behavior can be detected early enough for evasive actions. Similarly, greater visibility provided by good lighting enables people behaving in a suspicious manner to be identified and described with greater accuracy.

Lighting designed to allow action at a distance requires that attention be paid to the illuminance levels, the illuminance uniformity, the presence of disability glare, and the spectral power distribution of the light source. Recent research has shown that for people to have a reasonable perception of security at night in parking lots and on business streets, the horizontal illuminance on the pavement should lie somewhere between 10 and 50 lx (1.0 and 5.0 fc).⁵⁸ Below 10 lx (1.0 fc), perceptions of safety deteriorate rapidly. The principle of defensive action at a safe distance requires that vertical illuminance uniformity be within a ratio of 4:1, average to minimum, and 5 to 8 lx (0.5 to 0.8 fc) at 1.5 m above the ground. To achieve this goal, luminaires should provide illumination from more than one direction.

Disability glare is caused by light scattered in the eye. Care in the selection of luminaires and pole heights is essential if disability glare is to be avoided. Unfortunately, disability glare is common in public spaces, sometimes due to

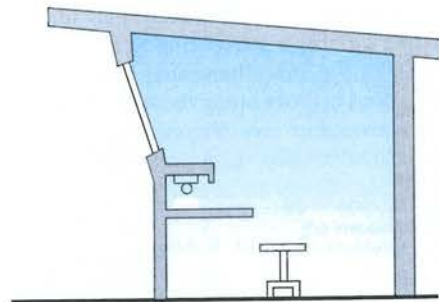


Figure 29-22. Gatehouses should be painted in dark colors and use well-shielded luminaires and tilted windows to minimize reflections and disability glare.

poorly aimed luminaires and often poor luminaire design. This is particularly true of some historical luminaires, which provide little shielding of the lamp and low mounting heights. In this case, low wattages should be used in the historical luminaires, and site illumination from other well-shielded sources should be used to meet security lighting design goals.

Light source spectral power distribution is important for seeing hair, eye, clothing, complexion, and vehicle colors, which are key elements in most witness statements. The ability to name colors accurately and confidently is determined by the light source spectral power distribution and the illuminance level. Research has shown that almost any nominally white light source ($CRI > 50$) allows accurate and confident color identification at the illuminances used in public spaces at night. High-pressure sodium lamps allow accurate but less confident color naming at high illuminances used for public spaces, but both the accuracy and confidence declines at lower illuminances. Low-pressure sodium lamps do not allow accurate color identification under any illuminance level.

Parking facilities. Techniques for lighting parking lots and parking garages are available in Chapter 22, Roadway Lighting, or IESNA RP-20-99, Lighting for Parking Facilities.⁵⁹ Walkways are discussed in IESNA DG-5-94, Lighting for Walkways and Class 1 Bikeways.⁶⁰ When security is an issue, because of crime history or changing conditions, the recommended minimum maintained security illuminance for open parking facilities should be no less than 30 lx (3.0 fc) on the pavement, with a uniformity ratio of 4:1, average to minimum. Vertical illuminance should also be 3 lx (0.3 fc) 1.5 m (5 ft) above the ground. These recommended values differ slightly from those offered in RP-20-99 for enhanced security. Functionally, however, the differences are unimportant. Sidewalks, footpaths, and grounds around open parking lots should be illuminated to a minimum of 6 lx (0.6 fc), with a uniformity ratio of 4:1, average to minimum. Vertical illuminance should also be 6 lx (0.6 fc) at 1.5 m (5 ft) above the ground.⁵⁹ These illuminances should be enough to identify a human face at 10 m (33 ft).

The threat to people and property in covered parking garages can be very high. This condition is caused by isolated floors, numerous places to hide, and a lack of effective surveillance. Recommended minimum illuminances for covered parking facilities should be no less than 60 lx (6.0 fc) on the pavement, with equal values measured vertically at 1.5 m (5 ft), and a uniformity ratio of 4:1, average to minimum. These illuminances should be maintained around the clock because daylight rarely penetrates deeply into parking garage.

Parks and public areas. Parks and public areas are areas where opportunity for violent crime is high. As with any other area where criminal activity is likely, the lighting system should enable action at a distance by illuminating potential hiding places and adjacent areas. Locations where loitering and graffiti are likely to occur should be uniformly

illuminated at least to 10 lx (1 fc) at ground level with an average-to-minimum ratio of 4:1. Planners also need to consider the following issues when designing the lighting and other components of security and safety management:

- Light pollution and light trespass
- Prior history of crime in the park and surrounding areas
- Social conditions and citizen participation
- Cultural values
- Traffic patterns and access
- Patrol frequency

Trails and walkways should be illuminated to a minimum of 6 lx (0.6 fc) at ground level, with an average-to-minimum uniformity ratio of 4:1 along the length of the trail and on all sides out to a distance of 10 m (30 ft). Vertical illumination 1.5 m above the ground should be at least equal to the horizontal illuminance at ground level. Where trails are situated in woods, landscape areas, or even broken terrain, lighting designers should also attend to aesthetic issues.⁶² Information on lighting for public parking lots, public walkways, and jogging trails can be found in Chapter 21, Exterior Lighting, and Chapter 22, Roadway Lighting.

Fast food restaurants. Many fast food restaurants are around-the-clock operations. The drive-through area is where criminals are most prone to attack, particularly when patrons are involved in transactions at the window. The attacker typically approaches the patron between the building and the left rear of the automobile. Building designs that allow the window service personnel to view the left sides of cars provide a deterrent to this type of mugging. Lighting that is mounted on the building, above the side window, allows good observation by the employee, although glare for the patrons in their cars should be avoided (Figure 29-23). Considering the vulnerability of drive-up customers at fast food locations and when security is an issue, lighting standards should exceed those described for parking lots discussed in RP-20-99⁵⁹ during all hours of operations. For these applications, the recommended minimum maintained illuminance for the area within 30 ft of the drive-up window(s) should be no less than 60 lx (6.0 fc) on the pavement with a uniformity ratio of 3:1, average to minimum. Sidewalks, footpaths, all areas adjacent to the structure, and the remainder of the parking lot should be illuminated to a minimum of 30 lx (3.0 fc) at grade, with an equal value measured vertically 1.5 m (5 ft) above grade and with an illuminance uniformity ratio of 4:1, average to minimum.

Convenience stores. Convenience stores often operate around the clock. When security is an issue the minimum recommended maintained horizontal illuminance should not be less than 60 lx (6.0 fc) on the parking lot pavement and customer use areas, including gasoline pumps and islands, air and water stations, and drive-up telephones. The illuminance uniformity should not exceed a ratio of 3:1, average to minimum. Surrounding, adjacent, or internal sidewalks,

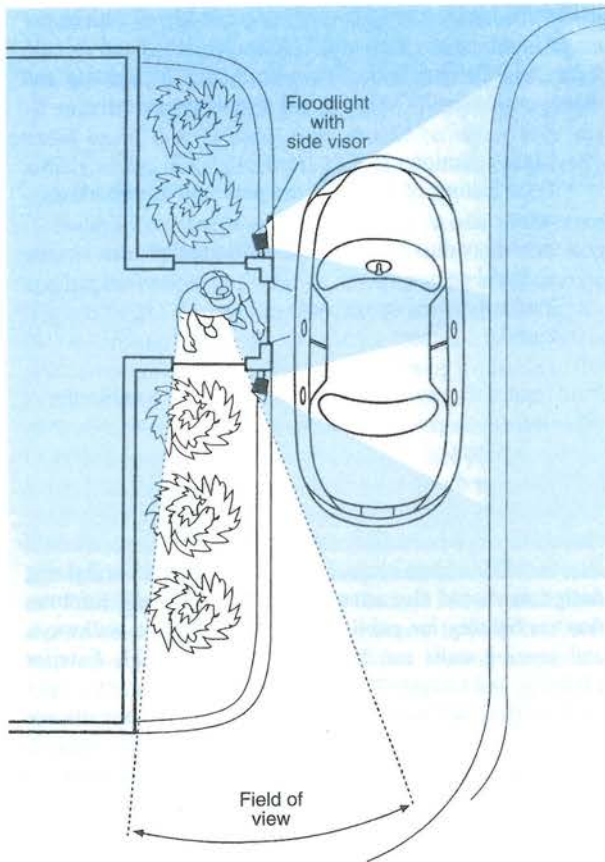


Figure 29-23. Location of luminaires for drive-up fast-food restaurant.

footpaths, refuse disposal area(s), areas adjacent to all sides of the structure, and grounds areas should be illuminated to a minimum maintained illuminance of 30 lx (3 fc) at ground level with a uniformity ratio of less than 3:1, average to minimum. It is recommended that the storefront exit and the sidewalk areas be lighted to a minimum of 50 lx (5.0 fc) at the pavement. If supplemental viewing devices such as surveillance cameras or mirrors are employed, a minimum vertical illuminance of 12 lx (1.2 fc), 1.5 m (5 ft) above ground level should be provided for lighting faces. Vertical illuminances in the parking lot improve the visibility of the outdoor parking area to people inside the store, provided the luminances of objects exceed the luminances of the reflections on the inside of the glass. Ambient lighting within the store is usually adequate for security purposes. Store management should always have a clear view of the outside sales area. After dark, more illumination is required outdoors than inside to prevent windows from acting as mirrors. Covering windows with opaque sales promotion posters should be discouraged. Reference should be made to IESNA RP-20,

Lighting for Parking Facilities,³⁹ for additional guidance in lighting convenience store parking facilities.

Automated teller machines and night depositories.⁶³ Automated teller machines (ATMs) and night depositories (NDs) present opportunities for criminals to perpetrate acts of crime against the public. ATMs and NDs do not normally provide security by professional personnel, so customer security must rely on physical security features such as lighting. As with any service where the public is invited to take advantage of unattended service locations, owners, operators, and providers of such services should adhere to applicable statutes or standards of security in an attempt to minimize risk to invited users. However, it is important to recognize that there are innumerable variables in site configurations, existing lighting applications, weather, seasonal impacts, and other conditions, which require some flexibility in the implementation of recommended practices. IESNA Design Guide DG-9-97, *Lighting for Automatic Teller Machines*,⁶⁴ and the section "Financial Facilities" in Chapter 11, *Office Lighting*, provide additional information on this subject. At the time of this printing, however, the standards for ATM/ND lighting are evolving. The reader should consult the IESNA and local codes for the latest information.

Security Lighting for Residences. The size of the residence, the distance from neighbors, the nature of the terrain, and whether the residence is in a rural, suburban, or urban area are all factors to be considered. Single-family housing and multifamily housing, such as an apartment building, have different security requirements and different security lighting needs. Deterrence is usually the number-one priority in residential security, followed by detection, recognition, and, if all else fails, a signal for help.

Deterrence. Security lighting can deter criminals by sending a message that at your residence the probability of detection and identification is high. To do this, enough light has to be provided to eliminate dark areas and to clearly reveal anyone on the property to a resident. Occupancy sensor controls are a key ingredient to deterrence in these applications.

Detection. To detect an intruder, there should be a high luminance contrast against the background. Lighting the landscape can achieve this by creating a bright background against which people can be seen. Illuminating exterior walls of a building makes it easier for neighbors to detect an intruder's silhouette against the lighted surface.

Signal for help. If deterrence has failed and an intruder has been detected outside, a call for help is desirable. Lighting can provide such a call. High-brightness strobe lights, located at eye level at points of entry and directed away from the residence, can interfere with the intruder, while providing an alarm to neighbors, passers-by, or patrols. Professional alarm or security equipment providers can furnish this equipment and integrate it into an existing electronic intrusion detection system.

Indoor lighting. Security lighting is not limited to exteriors. An intruder wanting to avoid confrontation may move to another target if the interior lights are on. Switching lights with a timer is one solution. This becomes more effective when the timer can be programmed to switch at different times during the week or month. Motion detectors that switch interior lights on when motion is detected are also effective. Illuminating critical interior entry or hallways can be effective deterrents and provide comfort to shut-ins and those who feel safer when the lights are on.

Single-family dwellings. The illumination of exterior doors is mainly for the identification of callers, for safety, and for more routine tasks such as finding keys quickly and locating lock keyways (Figure 29-24). Illumination from luminaires on both sides of the door aid in face recognition. If the luminaires are ceiling mounted, they should not be directly above or behind where the person would be standing. The minimum vertical illuminance for security lighting should be 8 lx (0.8 fc), measured 1.5 m (5 ft) above the doorway threshold.

Glare can be used effectively in residential applications if proper glare control techniques are used (Figure 29-25). Floodlights facing the street are a good deterrent, but they

should produce glare only to someone standing on the property. Passers-by (whether sidewalk pedestrians or drivers in cars) and neighbors should not be subjected to glare from the security lighting.

Side-yards, or set-backs, are best illuminated from the roof eaves or soffits of the residence. Mounting heights greater than 2.4 m (8 ft) are generally more difficult to defeat by vandals or intruders. Downlighting increases light levels on the face if the correct luminaires are employed. A long-life, high-luminous-efficacy light source, such as a low-wattage HID or CFL, is preferred. Lamps can be sensor controlled or manually operated to fit the needs of the residents. Luminaire spacing along the side of the building depends on the building shape, luminaire luminous intensity distribution, and the desired illuminance uniformity.

Walls, wooden fences, perimeter barriers, and similar features should be lighted from above, if possible. Plant materials can be uplighted to eliminate shadows or hiding spaces and for aesthetics. The illuminances in Figure 29-17 are a starting point for security lighting design for residential properties in high and low crime areas.

Multifamily residences. Multifamily residences present a security lighting challenge different from that for single

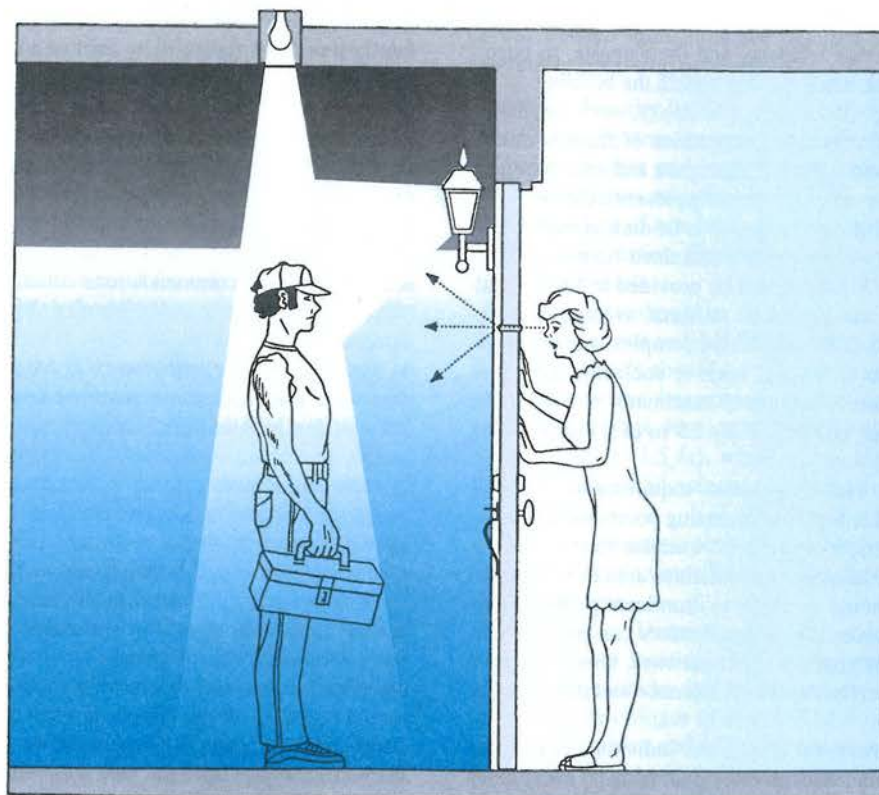


Figure 29-24. Location of luminaires for facial identification.

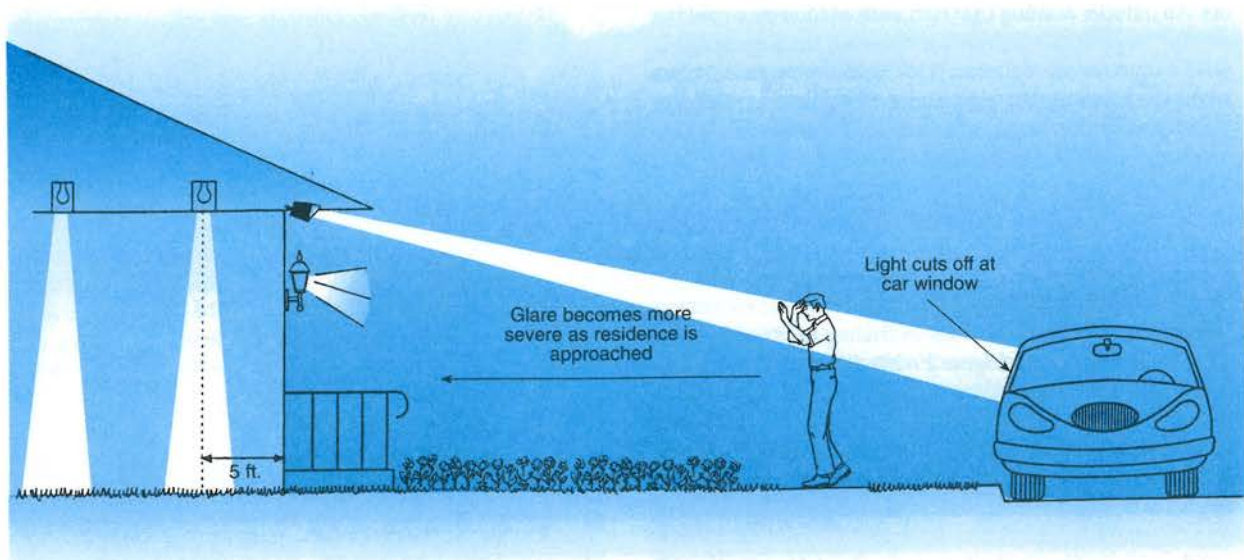


Figure 29-25. Techniques/goals for using glare as deterrent in residential applications.

family dwellings. Even when inside a structure, the occupants are not in a totally secure environment. The building is accessible to the other residents and their guests, so occupants may be at risk when moving within the building.

COMMON AREAS (HALLWAYS, STAIRWAYS, AND ASSEMBLY AREAS). Lighting that enables recognition of faces is essential to determine who belongs in the space and who does not, who is perceived as safe and who may present a danger. Corridors, hallways, and stairwells tend to be dark in many multifamily buildings. A minimum maintained horizontal illuminance of 30 lx (3.0 fc) should be provided at 1.5 m (5 ft) above floor level and should be uniform, average to minimum, at a 4:1 ratio. If the residential complex shares a common mail box area, the space, open or enclosed, should be uniformly illuminated, average to minimum, at a 4:1 ratio with a minimum of 100 lx (10 fc) 1.5 m (5 ft) above floor level.

OTHER AREAS. The illuminance requirements for mail rooms apply to other high-use gathering points such as laundry rooms, showers, locker rooms, exercise rooms, and the like, regardless of whether such facilities are closed or open in design. Care should be given to illuminate probable hiding or seclusion areas where perpetrators can prey on tenants. This includes spaces under stairways, unsecured storage lockers, roof access wells, and furnace and maintenance rooms.

INDIVIDUAL RESIDENCE CONTROLS. Individual residences must have, as a minimum, an individual lamp by every entry door for viewing potential visitors prior to opening the door. Regardless of whether visitors are viewed through a window or security viewing device (peep hole), the resident should

have sufficient illumination to clearly recognize facial features. Refer to the illuminance requirements for single-family dwellings for partially enclosed individual porches, patios, or privacy areas with entry doors to individual residences.

PARKING AREAS. Parking structures or open parking areas should be lighted in accordance with the recommendations of Chapter 22, Roadway Lighting and IESNA RP-20-99,⁹⁹ Lighting for Parking Facilities, under normal conditions. When security is an issue, lighting should be installed consistent with the recommendations contained in the sections "Parking Facilities" and "Security Lighting for Public Spaces" above.

MAINTENANCE CONSIDERATIONS. Maintenance of luminaires for a multifamily residential complex is a particularly vexing problem. Stocking the number and variety of lamps, vandalism, wear and tear, and tenants who intentionally circumvent security systems are just some of the problems faced by residence managers. Nevertheless, management must maintain a formal inspection routine and record keeping process for the repair and replacement of lighting equipment. These inspections should be performed no less than weekly, with a short turnaround time for repairs of no less than 36 hours. Formal records of the inspection process and the resulting repairs should be kept and referred to often. Where police or security officers work on the property, this inspection process should be performed on every shift for which an officer makes rounds and reported on his daily activity log or other forms. Also, if battery-operated lights are used, spare batteries and lamps should be available.

Lighting Equipment

Light Sources. Most general-purpose light sources can be used for security lighting. HID lamps are generally used for all-night security lighting. Because they provide the highest lumen package and the longest life, they are unaffected by most ambient operating temperatures and are available in a wide range of lumen ratings, spectral power distributions, and voltages. Some disadvantages: HID lamps require bulkier luminaires, control of light output is more difficult, initial cost is higher, and mounting may be more complex. These disadvantages can be offset by the benefits of needing fewer luminaires and having much longer lamp life.

The longer runup and restrike times of HID lamps make them unsuitable for use with motion sensors, or where lighting is energized only when an intruder is detected. In these situations, incandescent or fluorescent light sources are preferred. For more complete information on light sources and their individual characteristics, see Chapter 6, *Light Sources*, or refer to manufacturers' information for detailed lamp data.

Luminaires. Security lighting equipment can often suffer hazards more severe than weather and usage. Manufacturers provide a wide range of tamper-resistant and destruction-resistant systems. Other than intentional abuse, the selection of the luminaire is based on the light source to be used, the desired luminous intensity distribution, aesthetics, and the degree to which the luminaire is exposed to the environment. Environmental factors to be considered include whether the location is indoor or outdoors, temperature extremes, luminaire mounting location, and the level of vulnerability of the luminaire to damage by attack. Fluorescent sources are most affected by ambient temperature extremes. Most magnetic fluorescent ballasts are rated for use down to 10°C (50°F). If colder temperatures are expected, a cold weather electronic ballast rated for cold weather starting is necessary. Even though the lamps may start at cold weather temperatures, the lumen output of the lamp may be significantly reduced. Excessively warm temperatures also have an effect on fluorescent lamps, as lumen depreciation also occurs when ambient temperatures exceed 27°C (80°F). The designer should consult Chapter 6, *Light Sources*, and Chapter 7, *Luminaires*, with regard to sources and environmental factors.

In many situations, luminaires used for security lighting are part of the general lighting system, as in parking facilities or building enhancement. Frequently, the daytime appearance of the luminaire and pole is the deciding factor in the choice of equipment. Shopping malls may use more expensive equipment in public areas and lower-cost luminaires in employee areas. However, it is important to consider that employees usually arrive and depart when few customers are present, and therefore they may be subject to greater danger.

Regardless of luminaire type, the equipment must be easily maintained; if exposed to weather, it should be listed by

Underwriters Laboratories (UL) or the Canadian Standards Association (CSA) for wet locations. Luminaires may be mounted on poles, building surfaces, or on the ground. Where the luminaire may be subject to damage, vandal-resistant types should be installed.

Any luminaire mounted on a ceiling or wall and less than 3 m (10 ft) above the ground is likely to be the subject of physical abuse by vandals. A high-abuse luminaire should incorporate the following features:

- The base of the luminaire should have a step or flanged base and be solidly mounted to the building structure or mounting accessory.
- The electrical junction box should not be used as the sole luminaire support point.
- The lens or diffuser of the luminaire should be shatter proof and weather resistant.
- Exposed hardware should be tamper and weather resistant.
- The luminaire should have the ability to withstand repeated blows from an improvised club.

Lighting Poles. The higher luminaires are mounted from the ground, the fewer poles and luminaires are required to light a given area, and the lower the likelihood of vandalism. Fewer poles can cause more shadows and less uniform lighting, however. As pole heights are reduced, more poles with lower-wattage luminaires are required to avoid glare and nonuniform lighting patterns.

Controls. Security lighting should always be controlled automatically. System design should consider the possibility of power outages and lamp failure. Redundancy should be considered when assigning luminaires to control zones, so that the failure of one luminaire does not leave a large area without illumination. Further advice is given in Chapter 27, *Lighting Controls*.

HID systems should be designed to be energized prior to darkness at a time suitable for the runup period of the lamp. Lighting controls should be designed to energize the lighting system when the ambient natural lighting level is 1.6 times the average horizontal security illuminance design value, or 15 lx (1.5 fc), whichever is higher. This ensures that the designed illuminances are met during dusk as well as after dark.

Types of automatic controls suitable for security lighting operation include time clocks, photocontrols, dimmers, and motion detectors.

Time clocks. These are generally used to control large areas from one location, such as mall parking lots. Astronomical time clocks can be programmed to adjust on-off times with the changes of season. These types of clocks can be quite expensive and still may not be able to readjust by themselves if darkness is hastened by cloud cover. All time clocks should include a battery backup.

Photocontrols. These are used to control individual or small groups of luminaires on circuits, which are always en-

energized. They can be designed to automatically energize luminaires during dark periods regardless of time of day. They have the added advantage of not needing to be reset after power outages or before and after daylight-saving time periods. Photocontrols should not be mounted where the light sensing area is accessible to flashlight or vehicle headlight beams.

Dimmers. These can be used to reduce illumination and power demand by approximately 50% during low traffic periods in such applications as industrial employee parking lots during working hours or mall parking lots late at night. By dimming all units, the entire area remains uniformly illuminated. This contrasts with the spotty appearance commonly caused when half the luminaires are switched off to save electricity. Dimmable fluorescent and HID units require special ballasts. Dimmed HID sources may not have the same color characteristics as when they are operated at full output. This can have implications for camera surveillance as well as the ambiance of the space.

Motion detectors. These are used to switch on specific units when motion is detected. Motion detectors employ infrared or ultrasonic technologies to detect motion.⁶⁵ Infrared detectors are the predominant choice outdoors, due to the sensitivity of ultrasonic detectors to movement caused by wind. Due to the runup time of HID light sources, motion detectors should be used only with incandescent and fluorescent light sources.

Lighting for Camera Surveillance. Cameras do not have the same spectral sensitivity as the human eye, and therefore they respond differently to light sources. Most manufacturers specify a minimum illuminance needed for their cameras to produce a clear picture. These illuminances are usually given for an incandescent lamp and, most usefully, in terms of the amount of illumination on the image sensor. Higher illuminances are required for other light sources. Further, if moving objects are to be easily seen, illuminances above the minimum are required, whatever the light source. The manufacturer should be consulted before selecting the light source to be used, if there is any doubt about the sensitivity of the camera.

Cameras also have a rather limited dynamic range. Care should be taken to mount surveillance cameras below the luminaires, so that they do not receive any light directly from the luminaires causing "white-out" of that part of the image. In addition, all surfaces that are to be seen by the camera should be evenly illuminated. The security station containing monitors for surveillance cameras should also be carefully lighted to avoid reflections from interior luminaires in the monitor screens.

Site Assessment and Maintenance. Evaluations should be conducted regularly to determine what reasonable levels of security lighting and other security features or techniques should apply to each location. These surveys or audits should be performed annually, and at a minimum, they should include crime analysis of the location and surround-

ing community, physical and operational changes at the site, condition of the immediate community, and lighting configuration and maintenance on the property.

No security lighting system can remain effective without regularly scheduled maintenance. A planned maintenance program should include immediate replacement of failed lamps, repair or replacement of vandalized luminaires, regular cleaning, and cutting back of any encroaching vegetation. For additional information consult Chapter 28, Lighting Maintenance.

Lamp replacement. A well-designed security lighting system should have overlapping light patterns so that no area is dependent on a single luminaire. Failed lamps should be replaced immediately, however, in case a second lamp in the same area also fails. With installations requiring special lift equipment to service the luminaires building owners or managers should consider replacing all of the lamps at the same time.

Repair or replacement. Luminaires damaged by natural causes or vandalism should be immediately repaired or replaced. Luminaire condition should be monitored on a regular and frequent schedule to assure that all are working and aimed properly to produce the desired lighting coverage.

Cleaning. Regardless of the quality of the equipment, insects and dirt collect in enclosed luminaires. Therefore, all units should be cleaned at least once each year. A more frequent schedule should be followed when inspection indicates it is required.

Pruning. Shrubbery adjacent to walkways, driveways, alleys, and park areas must be pruned regularly to prevent interference with the light pattern and eliminate shadowed areas. Landscaping around buildings must be pruned regularly to prevent growth from obscuring potential intruders.

REFERENCES

1. Boyce, P. R. 1985. Movement under emergency lighting: The effect of illuminance. *Light. Res. Tech.* 17(2):51-71.
2. Boyce, P. R. 1986. Movement under emergency lighting: The effects of changeover from normal lighting. *Light. Res. Tech.* 18(1):1-18.
3. Jaschinski, W. 1982. Conditions of emergency lighting. *Ergonomics* 25(5):363-372.
4. Ouellette, M. J., and M. S. Rea. 1989. Illuminance requirements for emergency lighting. *J. Illum. Eng. Soc.* 18(1):37-42.
5. Simmons, R. C. 1975. Illuminance, diversity and disability glare in emergency lighting. *Light. Res. Tech.* 7(2):125-132.
6. Nikitin, V. D. 1973. Minimum required level of illumination intensity for emergency illumination in evacuation of persons. *Svetotekhnika* 6:9-10.
7. Ouellette, M. J., B. W. Tansley, and I. Pasini. 1993. The dilemma of emergency lighting: Theory vs reality. *J. Illum. Eng. Soc.* 22(1):113-121.
8. National Fire Protection Association. 1996. *Standard for health care facilities*, NFPA 99. 5th edition. Quincy, MA: National Fire Protection Association.

9. National Fire Protection Association. 1999. *National electrical code 1999*, NFPA 70. Quincy, MA: National Fire Protection Association.
10. Webber, G. M. B. 1985. Emergency lighting recommendations. In *Proceedings of the International Conference on Building Use and Safety Technology*, Los Angeles, CA, March 12-14, 1985. National Institute of Building Sciences.
11. Webber, G. M. B., P. J. Hallman, and A. C. Salvidge. 1988. Movement under emergency lighting: Comparison between standard provisions and photoluminescent markings. *Light. Res. Tech.* 20(4):167-175.
12. Webber, G. M. B. 1987. Way out lighting. *Build. Serv.* 9(8):39-40.
13. Webber, G. M. B., and P. J. Hallman. 1987. Emergency lighting and movement through corridors and stairways. In *Contemporary Ergonomics: Proceedings of the Ergonomic Society's 1987 Annual Conference*, Swansea, Wales, April 6-10, 1987. Edited by E. D. Megaw. London: Taylor & Francis.
14. Webber, G. M. B., and P. J. Hallman. 1988. Movement under various escape route lighting conditions. In *Safety in the built environment*. Edited by J. D. Sime. London: E. & F. N. Spon.
15. Green, L. 1986. Emergency lighting. *Specif. Eng.* 55(4):117-119.
16. Tiangsing, F. 1997. FAA Advisory Circular 25.812-2, Washington: Federal Aviation Administration.
17. Clark, F. R. S., M. S. Rea, and M. J. Ouellette. 1985. Visibility of exit signs through smoke. In *Preconference Proceedings: International Conference on Building Use and Safety Technology*, Los Angeles, CA, March 12-14, 1985.
18. Jin, T., S. Takahashi, S. Kawai, Y. Takeuchi and R. Tanabe. 1983. Experimental study on visibility and conspicuousness of an exit sign. *Proceedings: 21st session*. Commission Internationale de l'Eclairage, Venice, June 1987. Vienna: Bureau Central de la CIE.
19. Ouellette, M. J. 1992. Emergency lighting: A survey. *Canadian Property Management* 7(5):8-10.
20. U.S. National Bureau of Standards. 1978. *Smoke measurements in large and small scale fire testing*, NBSIR 78-1502. Prepared by R. W. Bukowski. Gaithersburg, MD: National Bureau of Standards.
21. Cooper, L. Y. 1995. Compartment fire-generated environment and smoke filling. Chapter 10 in *SFPE handbook of fire protection engineering*, 2nd ed. Quincy, MA: National Fire Protection Association.
22. Lighting Research Center. National Product Information Program. 1994-1998. *Specifer reports and supplements: Exit signs*. Troy, NY: Rensselaer Polytechnic Institute.
23. Rea, M. S., F. R. S. Clark, and M. J. Ouellette. 1985. *Photometric and psychophysical measurements of exit signs through smoke*, NRCC 24627. [Ottawa]: National Research Council Canada.
24. For a summary of Energy Star exit sign specifications, refer to U.S. Environmental Protection Agency. *What is an ENERGY STAR-labeled exit sign?* At <http://www.epa.gov/appdstar/exit/products.html>. Last updated January 12, 1999. For latest updates to exit sign specifications refer to: U.S. Environmental Protection Agency. *ENERGY STAR-labeled exit signs manufacturers*. At <http://www.epa.gov/appdstar/exit/manufacturers.html>. Scroll to bottom and download Memorandum of Understanding.
25. Webber, G. M. B., and C. E. Aizlewood. 1994. Investigation of emergency wayfinding lighting systems. *Light & Engineering* 2(3):82-94.
26. U. S. Congress. 1990. *Americans with disabilities act of 1990*, PL 101-336. Washington: U. S. Government Printing Office.
27. National Fire Protection Association. 1997. Illumination of means of egress, emergency lighting, and markings of means of egress. In *Life safety code*, NFPA 101, sections 5-8 through 5-10. Quincy, MA: National Fire Protection Association.
28. Underwriters Laboratories. 1998. Exit sign visibility. In *Standard for safety: Emergency lighting and power equipment*, UL-924-1995 (R1998). Northbrook, IL: Underwriters Laboratories, Inc.
29. Canadian Standards Association. 1996. *Performance of exit signs*, CSA C860-96. Etobicoke, ON: Canadian Standards Association.
30. Canadian Standards Association. 1992. *Unit equipment for emergency lighting*, CSA C22.2 No. 141 M1985(R1992). Etobicoke, ON: Canadian Standards Association.
31. Commission Internationale de l'Eclairage. 1981. *Guide on the emergency lighting of building interiors*. CIE Publication 49. Paris: Bureau Central de la CIE.
32. International Standardization Organization. 1984. *Safety colours and safety signs*, ISO 3864. Geneva, Switzerland: International Standardization Organization.
33. National Fire Protection Association. 1996. *Standard for Fire Safety Symbols*, NFPA 170. Quincy, MA: National Fire Protection Association.
34. U.S. National Bureau of Standards. 1983. *Evaluation of exit symbol visibility*, NBSIR 83-2675. Prepared by B. L. Collins and N. D. Lerner. Washington: National Bureau of Standards.
35. U.S. National Bureau of Standards. 1983. *Size of letters required for visibility as a function of viewing distance and observer visual acuity*, NBS TN 1180. Prepared by G. L. Howett. Washington: National Bureau of Standards.
36. Associate Committee on the National Building Code of Canada. 1995. Lighting and emergency power systems, Subsection 3.2.7; Exit signs, Subsection 3.4.5. In *National Building Code of Canada 1995*. Ottawa: National Research Council, Institute for Research in Construction.
37. U.S. National Institute of Standards and Technology. 1990. *Evaluation of exit signs in clear and smoke conditions*, NISTIR 4399. Prepared by B. L. Collins, M. S. Dahir, and D. Madrzykowski. Gaithersburg, MD: National Institute of Standards and Technology.
38. U.S. Department of Transportation. Federal Aviation Administration. 1999. *Emergency exit marking, emergency lighting, and emergency exit access*. 14 CFR 23.811-23.813. Washington: U.S. Government Printing Office.
39. Ouellette, M. J. 1988. Exit signs in smoke: Design parameters for greater visibility. *Light. Res. Tech.* 20(4):155-160.
40. Federal Aviation Administration. 1979. *Readability of self-illuminated signs in a smokeobscured environment*. FAA-AM-79-22, FAA-ARD-79-108. Prepared by P. G. Rasmussen, J. D. Garner, J. G. Blethrow, and D. L. Lowrey. Washington: Federal Aviation Administration.
41. Wilson, I. 1990. The effectiveness of exit signs in smoke. *Light. Aust.* (February):14-19.
42. Jin, T., and T. Yamada. 1985. Irritating effects of fire smoke on visibility. *Fire Sci. Tech.* 5(1):79-90.
43. Federal Aviation Administration. 1982. *Examination of air-*

- craft interior emergency lighting in a postcrash fire environment. DOT/FAA/CT-82/55. Prepared by J. Demaree. Washington: Federal Aviation Administration.
44. Beyreis, J. R., and T. G. Castino. 1974. Safety in sight. *Lab-data* 5(1):14-19.
 45. Ouellette, M. 1993. This way out: Conclusions from studies on exit sign illumination and visibility. *Progressive Architecture* 74(7):39-42.
 46. Collins, B. L. 1991. Visibility of exit signs and directional indicators. *J. Illum. Eng. Soc.* 20(1):117-133.
 47. Standards Association of Australia. 1983. *Emergency evacuation lighting in buildings. Part 1: Installation requirements*, AS2293, Part 1-1983. North Sydney, N.S.W.: Standards Association of Australia.
 48. U.S. National Eye Institute. 1983. *Vision research: A national plan 1983-1987*. Vol. 1. NIH/PUB 83-2469; NEI 80-306-1. Washington: National Institutes of Health.
 49. Hurvich, L. M. 1981. *Color vision*. Sunderland, MA: Sinauer Associates.
 50. Moon, P. [1936] 1961. *The scientific basis of illuminating engineering*. Reprint, New York: Dover Publications.
 51. California. Office of State Fire Marshall. [1985]. *A feasibility study on the placement of egress signage at lower positions than is currently common: A report to the California State Legislature by the Office of the State Fire Marshal in response to SCR 32*. [Sacramento]: Office of State Fire Marshall.
 52. Associate Committee on the National Fire Code, National Research Council Canada. 1995. *National Fire Code of Canada*. Ottawa ON: National Research Council Canada.
 53. National Fire Protection Association. 1999. *Standard for emergency and standby power systems*, NFPA 110. Quincy MA: NFPA.
 54. American National Standards Institute. 1998. *Safety color code*, ANSI Z535.1-1998. New York: ANSI.
 55. IES. Color Committee. 1980. Potential misidentification of industrial safety colors with certain lighting. *Light. Des. Appl.* 10(11):20.
 56. IES Security Lighting Committee. In press. *Security Lighting*, RP-33. New York: Illuminating Engineering Society of North America. Expected publication date is 2000.
 57. Boyce, P. R. 1979. The effect of fence luminance on the detection of potential intruders. *Light. Res. Tech.* 11(2):78-83.
 58. Leslie, R. P., and P. A. Rodgers. 1996. *The outdoor lighting pattern book*. New York: McGraw-Hill.
 59. IES Roadway Lighting Committee. Subcommittee on off-roadway facilities. 1998. *Lighting for parking facilities*, RP-20-1998. New York: Illuminating Engineering Society of North America.
 60. IES Roadway Lighting Committee. Subcommittee for Off Roadway Facilities. 1994. *Recommended lighting for walkways and class 1 bikeways*, IESNA DG-5-1994. New York, NY: Illuminating Engineering Society of North America.
 61. Boyce, P. R., and M. S. Rea. 1990. Security lighting: Effects of illuminance and light source on the capabilities of guards and intruders. *Light. Res. Tech.* 22(2):57-79.
 62. Moyer, J. 1992. *The landscape lighting book*. New York: John Wiley.
 63. American Bankers Association. 1994. *ATM security: A banker resource kit*. Washington: American Bankers Association.
 64. IESNA. 1997. *Lighting for automated teller machines*, IESNA DG-9-97. New York, NY: Illuminating Engineering Society of North America.
 65. Maniccia, D. 1997. *Specifier reports: Occupancy sensors*. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.